AD-A085 646 MITRE CORP BEDFORD MA F/G 17/7
LORAN NAVIGATION SYSTEM.(U)
MAY 80 J L HOWARD F19628-79-C-0001
UNCLASSIFIED M79-206 ESD-TR-80-121 NL

1 OF 1
AD
A085646

END
DATE
FILMED
7-80
DTIC

(18) ESD-TR-80-121 (17)

LEVEL II (12)

(14) M79-206

(9) Technical rept.

(6) LORAN NAVIGATION SYSTEM

(10) BY J. L. HOWARD

(11) MAY 1980

(12) 83

Prepared for

DEPUTY FOR SURVEILLANCE AND CONTROL SYSTEMS
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
Hanscom Air Force Base, Massachusetts

Project No. 6200
Prepared by
THE MITRE CORPORATION
Bedford, Massachusetts
Contract No. F19628-79-C-0001 (15)

REVIEW AND APPROVAL

This technical report has been reviewed and is approved for publication.

WILLIAM C. RUSTENBURG
AN/TRN-38 Program Manager
Air Traffic Ctrl Sys Directorate
Deputy for Surv'l & Ctrl Systems

DONALD H. SHUMAKER, Major, USAF
Asst Chf, Tactical Loran Div
Air Traffic Ctrl Sys Directorate
Deputy for Surv'l & Ctrl Systems

FOR THE COMMANDER

DAVID H. AMOS, Cdr, USCG
Chief, Tactical Loran Division
Air Traffic Ctrl Sys Directorate
Deputy for Surv'l & Ctrl Systems

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: ESD-TR-80-121	2. GOVT ACCESSION NO.: AD-A085 646
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): LORAN NAVIGATION SYSTEM	5. TYPE OF REPORT & PERIOD COVERED
	6. PERFORMING ORG. REPORT NUMBER: M79-206
7. AUTHOR(s): J. L. Howard	8. CONTRACT OR GRANT NUMBER(s): F19628-79-C-0001
9. PERFORMING ORGANIZATION NAME AND ADDRESS: The MITRE Corporation, P.O. Box 208, Bedford, MA 01730	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Project No. 6200
11. CONTROLLING OFFICE NAME AND ADDRESS: Deputy for Surveillance and Control Systems, Electronic Systems Division, AFSC, Hanscom AFB, MA 01731	12. REPORT DATE: MAY 1980
	13. NUMBER OF PAGES: 82
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

AN/ARN-92	LORAN-C/D	Tactical LORAN
AN/ARN-101	LORAN Warpage	
LORAN	Navigation	
LORAN-C	Radio Navigation Aid	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

LORAN is a highly accurate source of positioning information that can also be used for precision time reference. This report presents an overview of the LORAN navigation system for the general reader. Basic system characteristics and relationships provide a background in LORAN navigation and signal processing that applies to LORAN receivers in current use. Data for available LORAN transmitter chains are included with the report.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

ACKNOWLEDGMENTS

This report has been prepared by The MITRE Corporation under Project No. 6200. The contract is sponsored by the Electronic Systems Division, Air Force Systems Command, Hanscom Air Force Base, Massachusetts.

Page 2 blank

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

The term LORAN is an acronym derived from the words LOng RAnge Navigation. The original design concept has been extended to meet increasing requirements for accuracy, resulting in the development of three successive systems designated LORAN-A, LORAN-C, and LORAN-D.

LORAN-C and LORAN-D have matured to provide accurate and reliable positioning information. With the development of fully automatic receivers for LORAN-C and LORAN-D, system characteristics have become hidden to the general user of LORAN. This has contributed to a general lack of understanding of LORAN and its capabilities.

This report is an overview of the LORAN system and LORAN receiver signal processing. The material is organized in three levels of technical complexity: First, a basic discussion of system characteristics to familiarize the reader with LORAN; second, a more detailed description of the LORAN signal; finally, a review of signal processing in LORAN receiving systems. The four major areas of the report are

- The history of LORAN, together with the concepts for tactical LORAN operations,
- The basic principles of LORAN signal processing and navigation,
- Recent developments in LORAN, and
- Tactical LORAN systems in current usage.

1 Historical Background

Present-day LORAN, including both LORAN-C and LORAN-D, is the result of more than 30 years of system development. The need for a long-range, high-accuracy radio navigation system was apparent from the beginning of the Second World War. Conventional methods of navigation were then virtually useless for convoys and aircraft on antisubmarine patrol in the North Atlantic during fog and foul weather.

1.1 LORAN-A

The first and most widely known LORAN system used the frequency band just below 2 MHz. Because of the high attenuation rate of the 2 MHz signal over land, for all practical purposes the first system was useful only over sea water. At that time, however, the pressing need was for navigation at sea, and the system satisfied that need very well. For many years it was called "Standard LORAN" but is now designated "LORAN-A." The merit of the wartime system is evidenced by its continued service in many areas. Although numerous improvements have been made, the current LORAN-A is virtually identical to the system first flight-tested in 1942. By the end of World War II, more than 70 transmitting stations provided navigational coverage over nearly one-third of the earth's surface. Approximately 75,000 receiving units had been built and delivered by several manufacturers, and the Hydrographic Office had prepared 2.25 million LORAN charts. LORAN-A positioning accuracy is limited by the technique of manually matching the 2 MHz pulse envelopes, and expected accuracies range from 1 to 5 nautical miles.

1.2 LORAN-C

Toward the end of World War II the military needed navigational coverage over land and at greater ranges than those provided by LORAN-A. Although those needs were not satisfied until long after the cessation of hostilities, they initiated a series of developments that finally produced LORAN-C, a 100 kHz pulse navigation system. LORAN-C transmitters radiate a peak power, depending on coverage requirements, ranging from 300 kW to 2000 kW. They use either a 625 or 1350 foot top-loaded antenna. LORAN-C uses a grouped-pulse technique instead of the one-pulse LORAN-A format to achieve higher average radiated power and better signal detection characteristics. A pulse group for each station consists of 8 pulses spaced 1000 microseconds apart, while the master station has an extra pulse for visual station identification. LORAN-C is fundamentally a much more accurate system than LORAN-A because the receiver phase tracks the 100 kHz carrier within the pulse envelope. This technique is capable of repeatable accuracies to within 15 meters (50 feet) Circular Error Probable (CEP).

In 1957 the U.S. Coast Guard placed the first LORAN-C system in operation on the eastern coast of the United States. Since then the Coast Guard has installed and operated 10 additional LORAN-C chains. Current plans will provide LORAN-C service throughout the Coastal Confluence Zone of the United States. Included in the plans is the expansion of service through the Great Lakes and a reconfiguration of the original East Coast system. The following is a list of the 11 LORAN-C chains now operated by the U.S. Coast Guard:

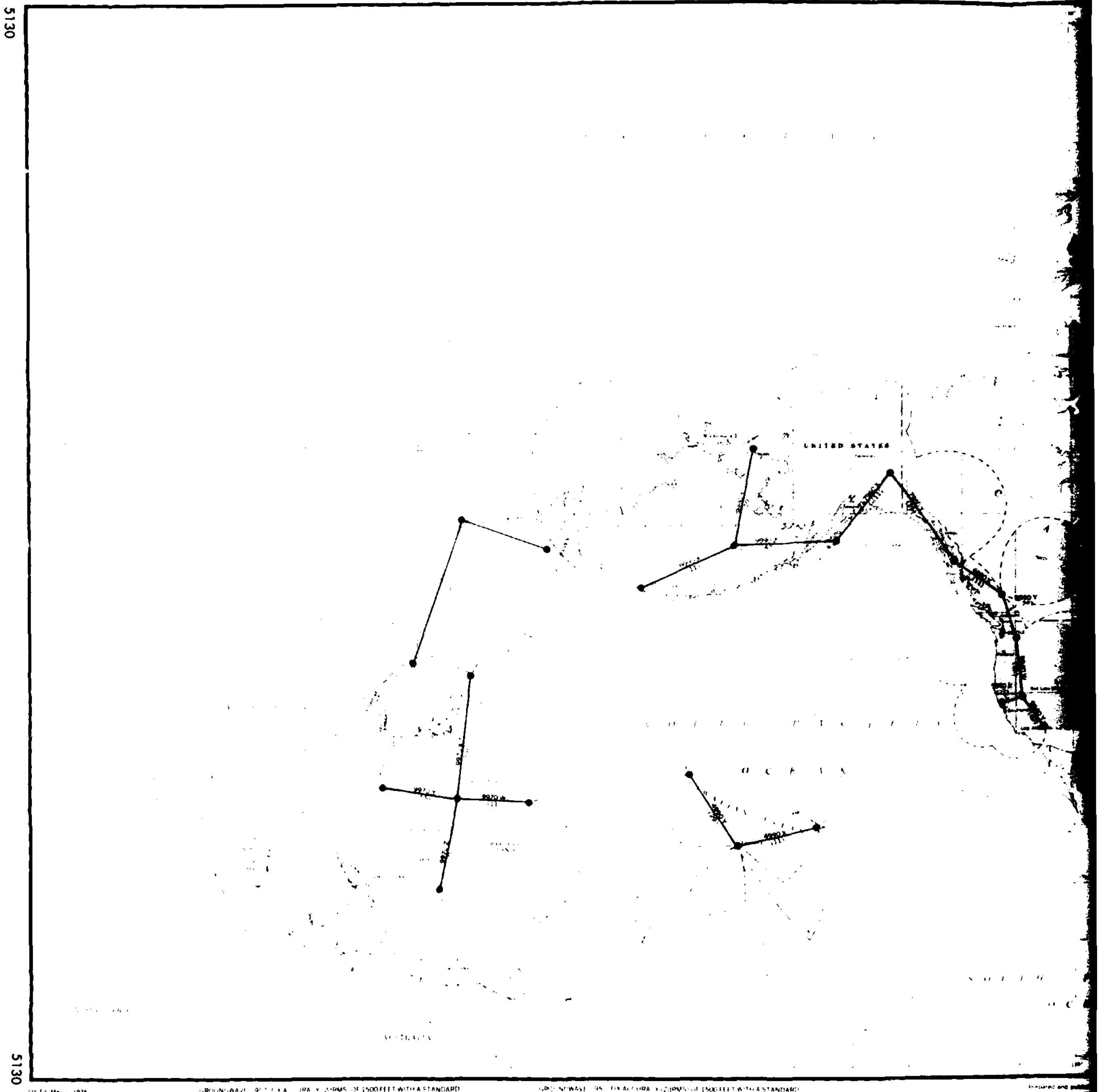
Central Pacific
Northwest Pacific
North Pacific
Gulf of Alaska
West Coast Canadian
U.S. West Coast
Southeast U.S.
U.S. East Coast
North Atlantic
Norwegian Sea
Mediterranean Sea.

Figure 1 illustrates the LORAN-C coverage provided by these 11 chains, and the Appendix provides the LORAN chain data needed for navigation.

Before 1980 a 12th chain will be added for the Great Lakes, and the U.S. East Coast chain will be reconfigured and called the Northeast U.S. chain. In addition to those government-operated chains, there are two privately owned, low-power (150-watt) chains. One chain provides coverage for the St. Mary's River, and the second is used for positioning information in the Gulf of Mexico. Their status after the Coast Guard expands its coverage of those areas is uncertain.

1.3 LORAN-D (Tactical LORAN)

In 1964 an Air Force Development Directive was issued to authorize development of a ground-referenced tactical navigation system based upon LORAN-C principles. Identified in Advanced Development as "LORAN-D" and in Engineering Development as "Tactical LORAN," this system is, in almost all respects, similar to and compatible with LORAN-C. LORAN-D is a tactical navigation system using ground stations that can be transported to an area and set up to provide LORAN coverage. The more compact LORAN-D transmitter generates a lower power signal than LORAN-C (7 to 30 kW) and uses a reduced antenna tower height (400 feet). To



MODIFIED

ATMOSPHERIC NOISE VALUES USED TO COMPUTE AREA RANGE LIMITS WERE DERIVED FROM INTERNATIONAL RADIO CONSULTATIVE COMMITTEE (CCIR) REPORT 322 1963

NOTE: The expansion of LORAN-C coverage in the United States is indicated by broken lines.

July 1979 - Reconfigure East Coast (9930) to Northeast (9960), and eliminate Cape Race, Newfoundland (9930X) slave.

Feb 1980 - Establish Great Lakes chain (9930)

Figure 1. LORAN Coverage Diagram

page 12 blank

compensate partially for the reduction in peak radiated power, LORAN-D uses a transmission of 16 pulses per station group spaced at 500 microseconds to improve detectability. LORAN-D, because of its lower peak radiated power, has a shorter maximum operating range than LORAN-C. The term "LORAN-C/D" is used to refer to those systems capable of operating on either LORAN-C or LORAN-D signal formats.

Currently, the Air Force operates two LORAN-D chains. One commercial chain provides coverage for the Utah test range, and the second, AN/TRN-21, provides tactical coverage for Central Europe. The Army owns and operates for training one LORAN-D chain near Fort Hood, Texas. The Air Force is building three LORAN-C/D chains, AN/TRN-38, which can be transported to provide tactical LORAN capability for regions where LORAN coverage presently does not exist.

2 System Characteristics

The LORAN system of navigation comprises transmitter chains, each consisting of a master and two or three secondary transmitters, which transmit groups of pulsed signals at a carrier frequency of 100 kHz. The group repetition interval (GRI) for a given chain is fixed somewhere between 39.3 and 100 milliseconds. The LORAN pulse has an envelope shape like a rounded-off triangular waveform, which reaches peak amplitude in 65 microseconds and has a long decay tail of 200 microseconds. The 100 kHz carrier in the pulse is bi-phase coded with 0 degree or 180 degree phasing, for purposes of skywave cancellation and other signal-processing operations within the receiver. For identification purposes the phase code of the master transmitter is different from that of the secondary transmitters. The master and secondary phase codes repeat every two LORAN GRIs for LORAN-C and every two or four LORAN GRIs for LORAN-D. The signal transmission times for the stations of a chain are synchronized so that each secondary station transmission follows the master transmission after a predetermined delay or waiting time after the master transmission. Multiple pulses in each station group are used so that more signal energy is available at the receiver. This technique significantly improves the signal-to-noise ratio (S/N) without having to increase the peak transmitted power capability of the transmitters.

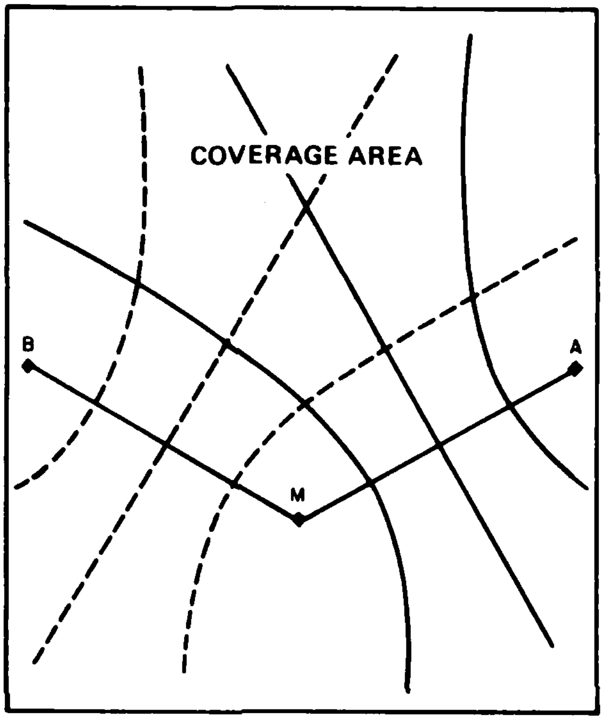
2.1 Fundamental Relationships

Hyperbolic radio navigation systems operate on the principle that the difference in time of arrival of signals from two stations, observed at a point in the coverage area, is a measure of the difference in distance from the point of observation of each of the stations. The locus of all points

having the same observed difference in distance to a pair of stations is a hyperbolic line of position (LOP). The intersection of two or more LOPs defines the position of the observer. The accuracy of any hyperbolic radio navigation system depends on the ability of observers to measure the difference between the times of arrival of two signals (time difference, or TD); it also depends on their knowledge of the propagation conditions and the exact location of the transmitters so that the time differences can be converted to LOPs.

LORAN chains may be "linked" to provide continuous coverage over extended areas, as shown in the LORAN-C coverage diagram (figure 1). The procedure requires that a LORAN station be "shared" by two different LORAN chains; the station is then dual-rated and operates synchronously with the two different GRIs of each LORAN chain. In this mode, the dual-rated station transmits two groups of LORAN pulses, one group synchronized to one LORAN chain and the second group synchronized to the other LORAN chain.

When discussing LORAN in general and when referencing signal processing in a LORAN receiver, the stations and time differences are identified by the Master (M) and Secondaries A and B. Thus, TDA is always first in time before TDB, and both terms are used interchangeably with specified station TDs. The LORAN transmitters generate an electronic grid, as illustrated in figure 2, which consists of families of crossing hyperbolas or LOPs.



A-54,204

Figure 2. Hyperbolic Lines of Position

The transmitting stations are located so that the signals from the master and at least two secondary stations can be received throughout the desired coverage area. The coverage area is normally defined by the included angle of the secondary-master-secondary baselines. When referencing a specific chain, the master station is designated by the letter M and the secondary stations are designated W, X, Y, or Z. Thus, a particular master-secondary pair and the TD that it produces can be referred to by the letter designations of both stations or just that of the secondary (e.g., MX time difference or TDX). A monitor station measures the timing adjustments necessary for the transmitters to maintain synchronism of the LORAN chain.

2.1.1 Frequency

In identifying a proper frequency for a radionavigation system that will give wide coverage and high accuracy, various physical factors must be considered. Since the velocity of propagation of radio energy is approximately one foot per nanosecond (1 ft/nsec), accuracies on the order of tens or hundreds of feet require measurements to tens or hundreds of nanoseconds. Propagation conditions must be reliably predictable (mathematically or from survey) to tens or hundreds of nanoseconds to satisfy the requirements for precision navigation. The large coverage areas of LORAN are made possible by the low propagation losses of LF groundwaves and the resultant long baseline lengths (station-to-station separation).

To take advantage of the stable propagation characteristics and long range of the LF band, 100 kilohertz (kHz) was chosen as the center frequency of the LORAN-C system. The LORAN-C pulse shape is such that greater than 99 percent of the radiated energy is contained between the frequencies of 90 and 110 kHz, as shown in figure 3.

2.1.2 Groundwave and Skywave Signals

The function of the LORAN receiver is to receive the signals of three stations and measure precisely the difference in time of arrival between the master and each secondary signal. The receiver will receive skywave as well as groundwave signals, as shown in figure 4.

The skywave signals arrive later in time than the groundwave signals. Skywaves from the first hop can be of short delay, with as little as 35 microseconds, or of long delay, with as long as 1000 microseconds. A skywave can overlap the groundwave that was transmitted simultaneously with it or a later groundwave pulse, depending on whether it is first, second,

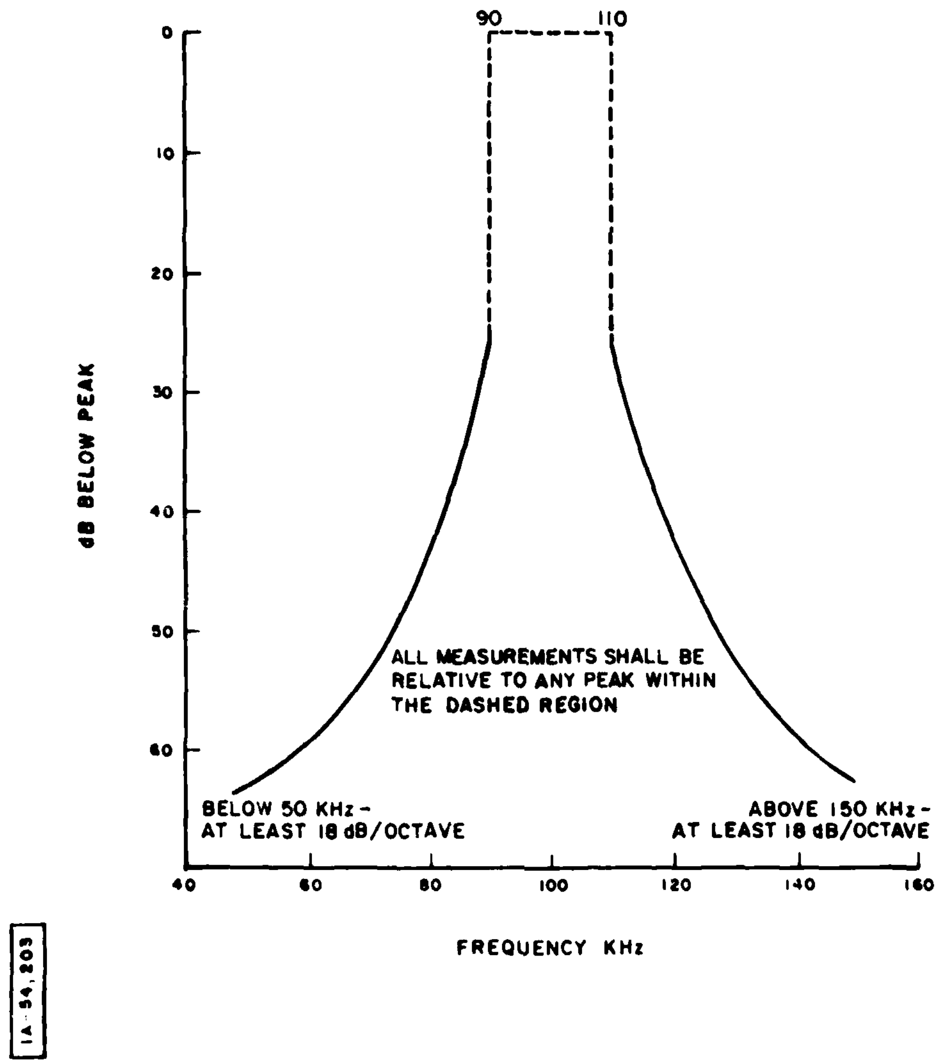


Figure 3. Prescribed LORAN Signal Spectrum Limits

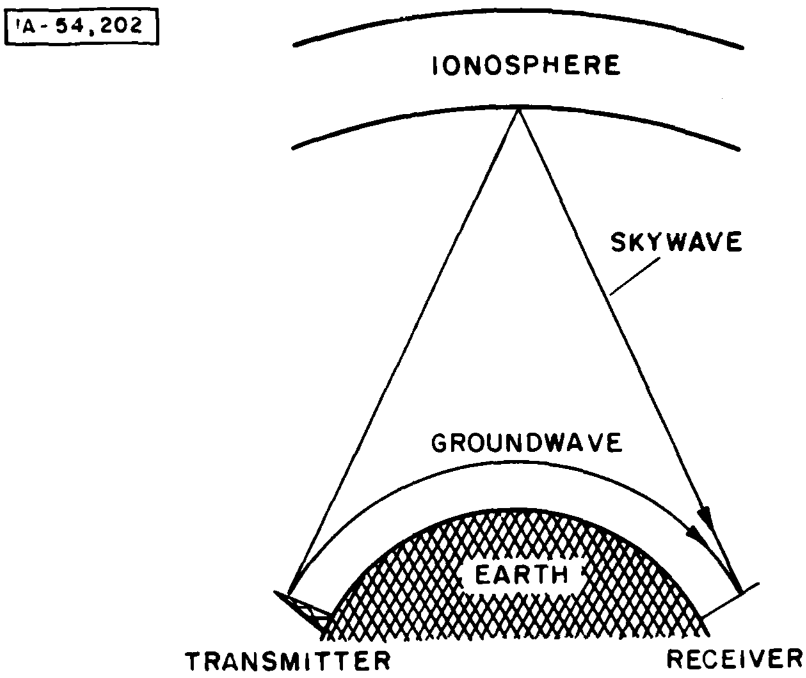


Figure 4. LORAN Groundwave and Skywave Signals

or later hop skywave. The receiver must select the highest amplitude cycle of the groundwave signal that is free of short-delay skywave contamination on all stations for an accurate time-of-arrival measurement. The third cycle of the groundwave is free of first-hop skywaves even at the long ranges of LORAN-C operation.

2.1.3 Timing and Coding Delays

The stations of a LORAN chain transmit groups of pulses at a specified GRI. For each chain, a minimum GRI is selected of sufficient length that it contains time for transmission of the pulse group from each station plus time between each pulse group, so that signals from two or more stations

cannot overlap in time anywhere in the coverage area. This concept is illustrated in figure 5. Thus, with respect to the time of arrival of the master, a secondary station will delay its own transmission for a specified time, called the secondary coding delay.

IA-54,197

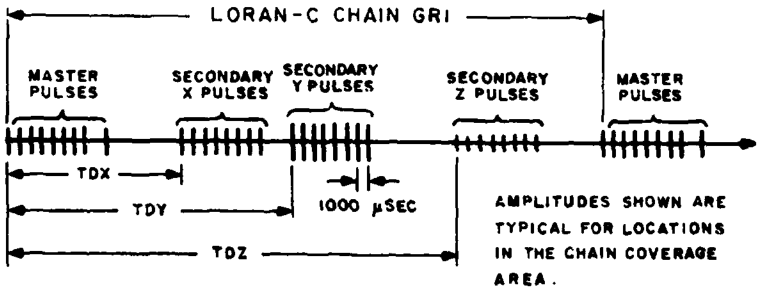


Figure 5. Example of Received LORAN-C Signal

The minimum GRI is therefore a direct function of the number of stations and the distance between them. Permissible values for GRI are listed in table 1. Each station in the LORAN chain transmits one group of pulses during each GRI. For LORAN-C, the master pulse group consists of 8 pulses spaced 1000 microseconds apart, and a 9th pulse for identification 2000 microseconds after the 8th pulse. The secondary pulse groups contain 8 pulses spaced 1000 microseconds apart. For LORAN-D all groups consist of 16 pulses spaced 500 microseconds apart.

The theoretical rate structure for LORAN is restricted to GRIs of less than 100,000 microseconds. In actual practice the selected GRIs are

Table 1

Group Repetition Intervals (GRI in Tens of Microseconds)*

9999	8999	7999	6999	5999	4999
9998	8998	7998	6998	5998	4998
9997	8997	7997	6997	5997	4997
⋮	⋮	⋮	⋮	⋮	⋮
9991	8991	7991	6991	5991	4991
9990	8990	7990	6990	5990	4990 (S1)
9989	8989	7989	6989	5989	4989
⋮	⋮	⋮	⋮	⋮	⋮
9971	8971	7971	6971	5971	4971
9970 (SS3)	8970	7970 (SL3)	6970	5970 (SH3)	4970 (S3)
9969	8969	7969	6969	5969	4969
⋮	⋮	⋮	⋮	⋮	⋮
9931	8931	7931	6931	5931	4931
9930 (SS7)	8930	7930 (SL7)	6930	5930 (SH7)	4930 (S7)
9929	8929	7929	6929	5929	4929
⋮	⋮	⋮	⋮	⋮	⋮
9000	8000	7000	6000	5000	4000

*Old GRI code shown in parentheses.

restricted to lie between 39,300 and 100,000 microseconds in 10 microsecond steps, being constrained by geometry and the presence of neighboring electromagnetic systems. Coding delay assignments and basic rate assignments of a chain are governed by the following criteria:

- Master-to-slave* and slave-to-slave separation will be at least 2500 microseconds in all parts of the service area. This is standard to allow a time interval for strong master 9th pulse skywaves prior to reception of the first slave signal. It also allows a time interval for strong slave 8th pulse skywaves prior to the first pulse of the slave or master pulse group that follows.
- The highest LORAN rate (lowest GRI) permitting this separation is generally used to provide maximum LORAN data rate and to minimize mutual (cross-rate) and CW interference.

2.1.4 Blink

Blink is a procedure used to warn users of the LORAN system that there is an error in the transmissions of a particular station.

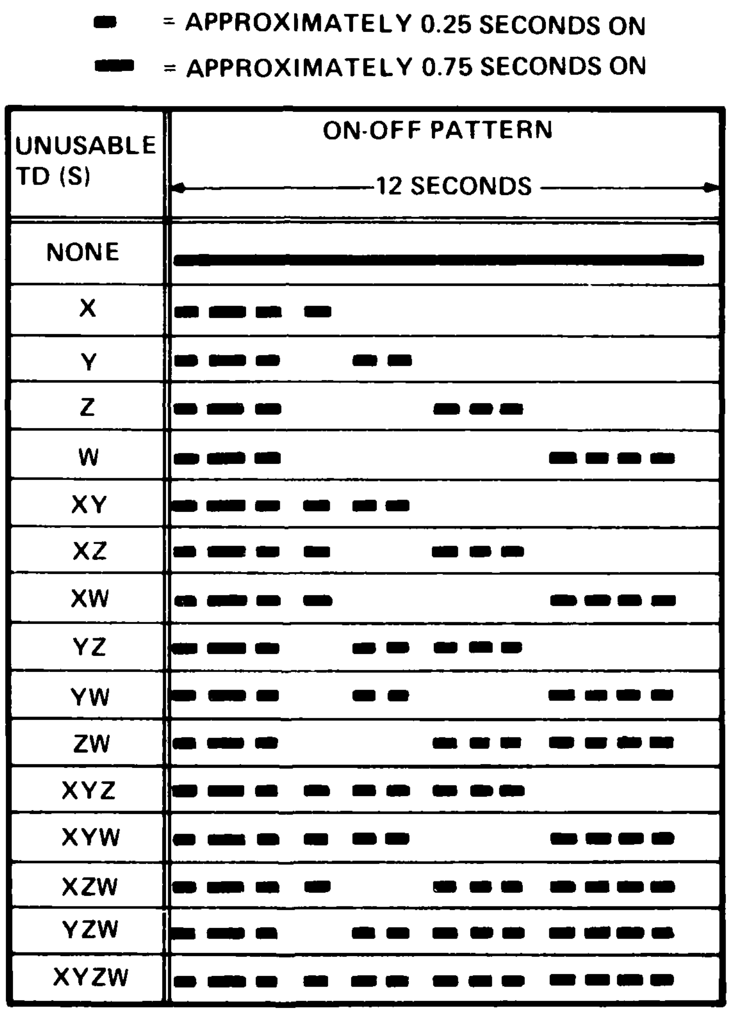
In LORAN-C the 9th pulse of the master station is turned on and off in a specified code that identifies the unusable TDs. The LORAN-C master blink code is shown in table 2. The duration of the short "on" portion is approximately 0.25 seconds and the duration of the long "on" portion is approximately 0.75 seconds. The affected LORAN-C secondary transmitter blinks the first two pulses of the secondary group. The duration of the "on" period is approximately 0.35 seconds out of every 4 seconds. All secondaries use the same blink procedure.

* The terms "slave" and "secondary" are used interchangeably.

Table 2

LORAN-C Blink Code

MASTER BLINK PATTERN – NINTH PULSE ONLY



IA-54,493

The LORAN-D blink procedure is different in that only the malfunctioning transmitter station turns off the first 4 pulses of the group during malfunctions. All LORAN-D transmitter stations use the same blink procedure.

Blink was initially designed for visual observation using manual LORAN-C receivers. This was one of the major functions of the 9th pulse of the LORAN-C master station. Most automatic receivers detect secondary station blink only, as this is sufficient to trigger alarm indicators.

2.2 Basic LORAN Equations

All LORAN navigation is based on the calculation of the intersections among the time difference (TD) LOPs. Consider a pair of LORAN stations, master M and slave S, and receiver R as shown in figure 6, and assume that stations M and S transmit simultaneously. Since point R is on the perpendicular bisector of the baseline, distances MR and SR are equal and the travel time of the radio waves over these paths will be equal ($t_{MR} = t_{SR}$). Therefore, the TD between the signals received from M and S equals zero (i.e., TD = $t_{MR} - t_{SR}$). At point B the TD is $t_{MB} - t_{SB}$, and at point C the TD is $t_{MC} - t_{SC}$. Since points B and C may measure the same TD and yet be on different LOPs, the simultaneous transmission will make the correct LOP uncertain. This difficulty is eliminated by

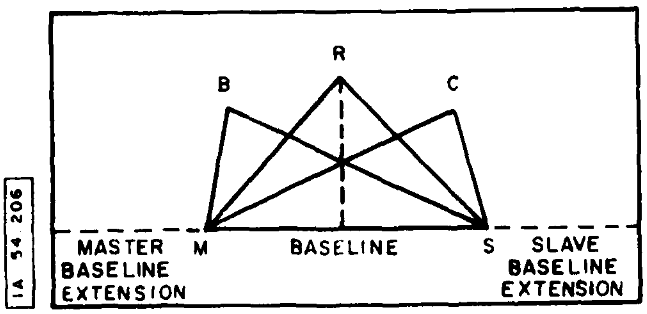


Figure 6. LORAN Time Difference Diagram

delaying the slave transmission until the master signal is received at that slave. When the master signal has been received by the slave, the slave station is allowed to transmit. As illustrated in figure 6, the TD is $t_{MS} + t_{SB} - t_{MB}$ at point B, and $t_{MS} + t_{SC} - t_{MC}$ at point C. The hyperbolic pair are now sequenced for practical operation and contain no ambiguities. An additional delay is also included to prevent signal overlap with other stations regardless of the receiver position in the coverage area; it is called the slave coding delay.

With this timing technique, the minimum time difference reading occurs on the slave baseline extension and is equal to the slave coding delay. The maximum time difference reading occurs on the master baseline extension and is equal to twice the baseline travel time plus the slave coding delay, or 2MS + slave coding delay. Figure 7 depicts the coding delays (CDs) of a generalized LORAN triad consisting of a master and slaves A and B. The transmitting sequence is as follows: (1) the slave stations receive a burst of pulses (rf energy) from the master station at times T_A and T_B, respectively, for each slave; (2) slave A delays its transmission from the master transmission for a predetermined time CDA (in μsec); (3) slave B delays its transmission for a predetermined time CDB, slightly longer than CDA: (4) a LORAN user in the chain area receives signals from all stations in the chain on the 100-kHz carrier frequency. The coding delays prevent interference with or overlaps of the bursts of rf energy from the three stations.

No matter how many secondary transmitters are used with a LORAN chain, LORAN position fixing is done by using the master and only two secondary stations. The LORAN receiver measures the time of arrival of each of the three stations, Master, Secondary A, Secondary B, and calculates the time difference for each master-secondary pair (TDA and

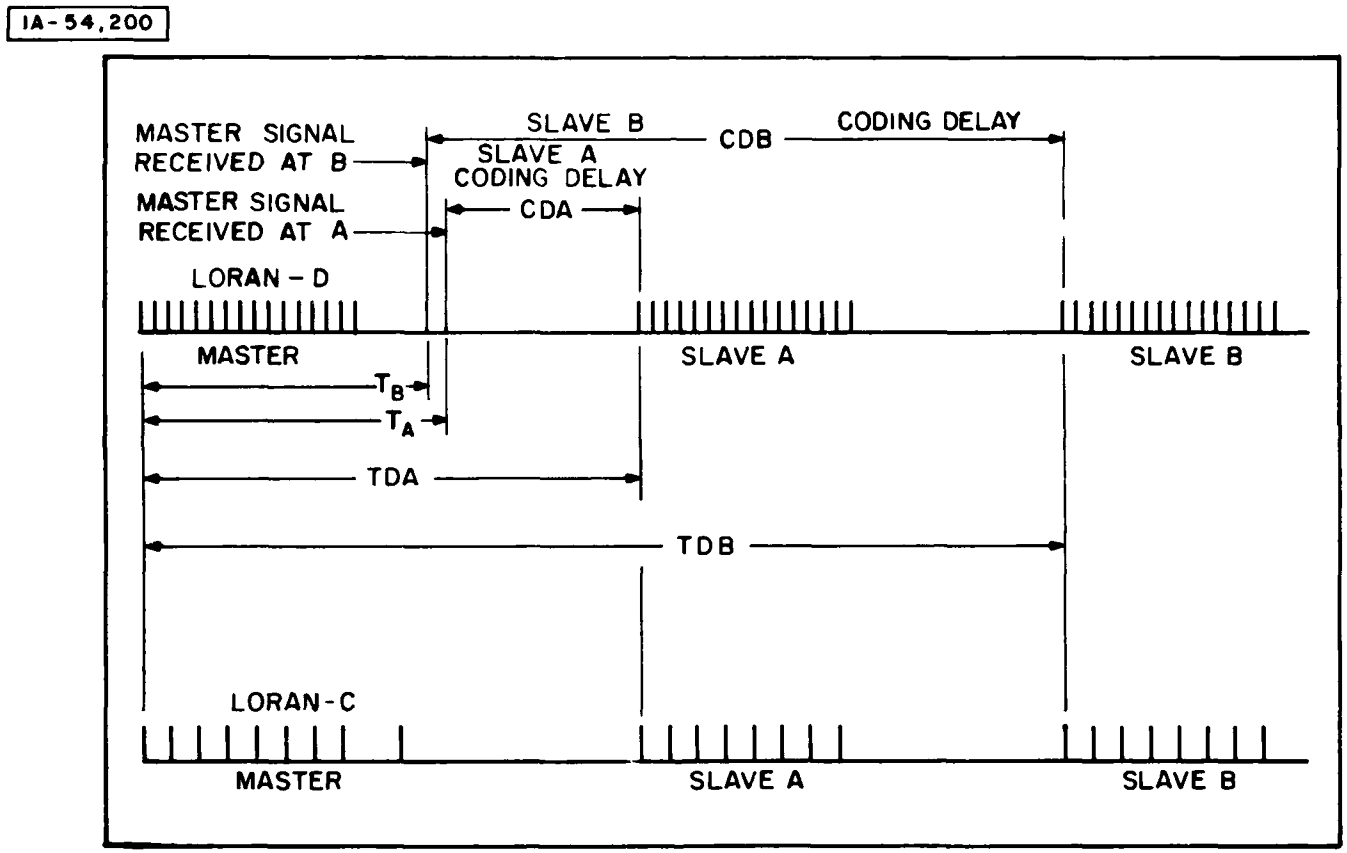


Figure 7. LORAN-C and LORAN-D Coding Delays

TDB). Each TD number represents the locus of all positions where the TD is constant. A unique position fix is obtained by using paired TD numbers. This hyperbolic fix with LORAN is illustrated in figure 8.

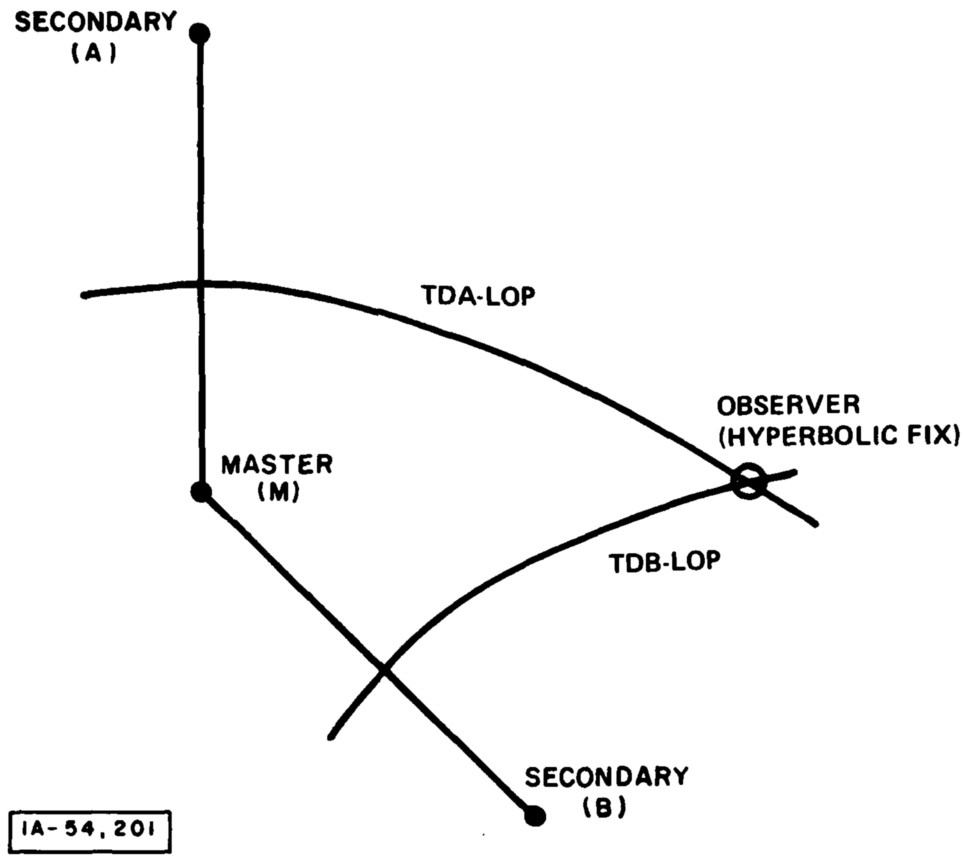


Figure 8. Hyperbolic Fix with LORAN

The prediction of LORAN TDs for any geographic position is a "closed form" solution with the following operations: (1) calculating the distance to each transmitter, (2) calculating the primary wave, (3) calculating and adding the secondary phase correction for each path, and (4) taking the difference between the slave and master propagation times and then adding the coding delay and baseline propagation times to the difference.

2.3 Propagation

The useful LORAN radio pulses are propagated by a groundwave that travels in contact with the earth's surface, and the measured time differences are related to ground distances from the transmitter to the receiver. LORAN signals are also propagated upward and are reflected by the ionosphere to earth as a skywave, as illustrated in figure 4. Time delay measurements based on skywave transmission are not so predictable or accurate as the undistorted groundwave signal.

2.3.1 Time of Arrival Calculations

In the original concept of the hyperbolic navigation system, it was assumed that the time differencing procedure would theoretically cancel all propagation errors and provide an electronic navigation grid that was directly related to a geodetic navigation grid. In actual practice, the cancellation is never complete and the electronic LORAN grid is not compatible with the geodetic grid. The measured TDs are subject to noncancelling errors due to the nonuniformity of the propagation paths from the receiver to each transmitter. These errors are influenced by the ground conductivity, terrain roughness, and the altitude at which the position fix is made. Additional propagation errors are associated with the dynamics of airborne vehicles, such as the effects of direction of flight, altitude, and antenna phase center movement. The latter errors may be compensated for, if altitudes and target approach directions for flight measurements are judiciously chosen and the errors are accordingly calibrated. Of all potential errors in LORAN TD measurements, the most difficult to compensate for when converting to latitude and longitude are those related to propagation anomalies, since they vary with location, altitude, and time.

LORAN propagation times can be calculated for each transmitter by considering time delays of both the primary wave and the secondary phase effects. The total propagation time between a transmitter and a reference position is computed as

$$T_S = T_{ps} + T_{cs} ,$$

where

T_S = propagation time for a LORAN signal between the transmitter and a reference position,

T_{ps} = primary wave contribution = $\dfrac{\text{distance between positions}}{\text{wave propagation velocity}}$,

T_{cs} = secondary phase contribution (warpage).

The primary wave calculation is based on free-space propagation and, if all other errors were cancelled, would provide accurate TD coordinates. However, because of the noncancelling effects, further corrections are needed to account for ground conductivity and to compensate for earth curvature. Figure 9 simply illustrates this secondary phase correction for different homogeneous conductivity (σ) media assuming a permittivity value of 15 (E_p = 15), as a function of range from a LORAN transmitter. The salt water conductivity model for the secondary phase correction is relatively simple, and algorithms for this model have been programmed into several LORAN receivers that provide latitude and longitude outputs. Although the secondary phase correction relates directly to the medium of the propagation path, the salt water model has sometimes been accepted as a standard. Consequently, corrections beyond salt water corrections

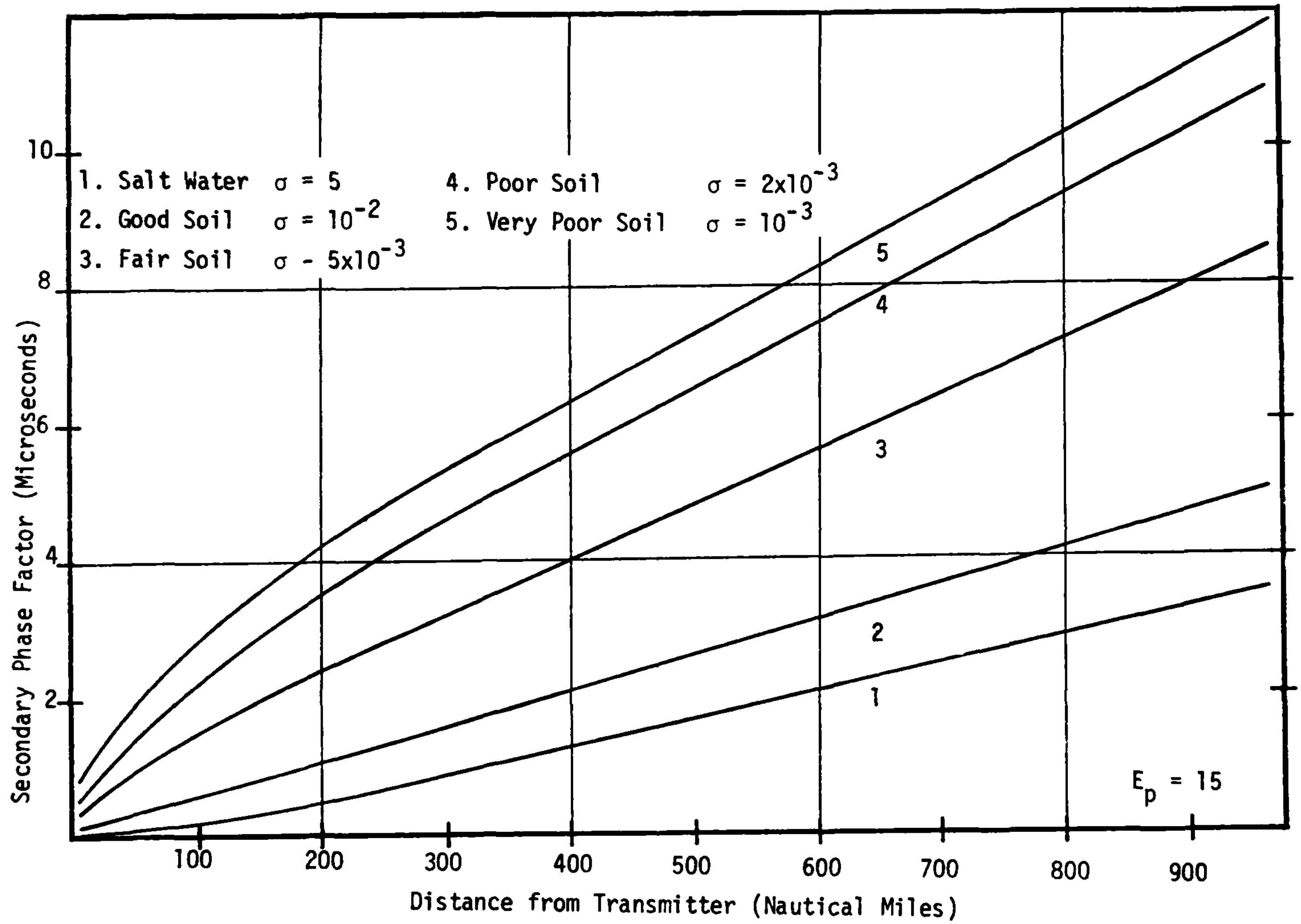


Figure 9. LORAN Secondary Phase Factor (NBS CIR 573)

are sometimes termed additional secondary phase (ASP) corrections. Other factors causing secondary phase effects are the ground conductivity variations resulting from such natural sources as earth strata irregularities and such man-made structures as power lines.

2.3.2 LORAN Warpage

Differences between TDs measured with a receiver and TDs calculated using secondary phase corrections from a homogeneous LORAN conductivity model can be interpreted as irregularities in the actual hyperbolic LOP. This condition is referred to as warpage. LORAN warpage occurs whenever the propagation medium is not uniform or the propagation path has multiple crossings of the interface of two different mediums, i.e. from land to sea. Although warpage is always present in LORAN TD measurements, it does not directly affect receiver operation or degrade the accuracy or repeatability of the time of arrival measurements in the electronic LORAN grid. However, warpage does affect the relationship between the LORAN hyperbolic grid and the geodetic (latitude, longitude) navigation grid. This relationship is further detailed as part of the discussion of accuracy and coverage area.

2.3.3 Field Intensity

The propagation medium also attenuates the transmitted LORAN signal according to the type of medium. Figure 10 was taken from NBS Circular 573 and illustrates the attenuation of the LORAN signal for propagation media ranging from salt water to very poor soil, assuming $E_p = 15$. Figure 10 is based on an effective radiated output of 300 kW. To adjust the field intensity to other output levels, the following conversion can be used if field strength is in voltage units of microvolts per meter. However, it cannot be used for decibel conversion.

$$\begin{pmatrix}\text{Field strength to} \\ \text{be used with curve}\end{pmatrix} = \begin{pmatrix}\text{Field strength} \\ \text{for 300 kW}\end{pmatrix} \times \sqrt{\frac{\text{Radiated power in kW}}{\text{300 kW}}}$$

2.4 Accuracy and Coverage Area

Overall system accuracy is a function of the following three major factors:

(1) Geometric Accuracy — The geometric accuracy of the system is dependent upon the very accurate positioning of the ground stations and their location relative to each other. The total effect is called the geometric dilution of precision (GDOP) and is expressed in terms of meters per microsecond of time difference. In general, GDOP error increases with distance from the center of the LORAN chain.

(2) Instrumentation Accuracy — The inherent measurement capability of most receiver systems in a noise environment has been determined to be less than 0.05 microsecond, depending on signal and noise conditions, calibration, etc.

(3) Propagation Accuracy

(a) Variations that occur in groundwave propagation are usually less than 0.1 microsecond over a 1000-mile sea water path;

(b) Variations that occur in skywave propagation are nominally 1 to 1.5 microseconds from a mean predicted value, except at sunrise and sunset, at which times large and rapid variations occur.

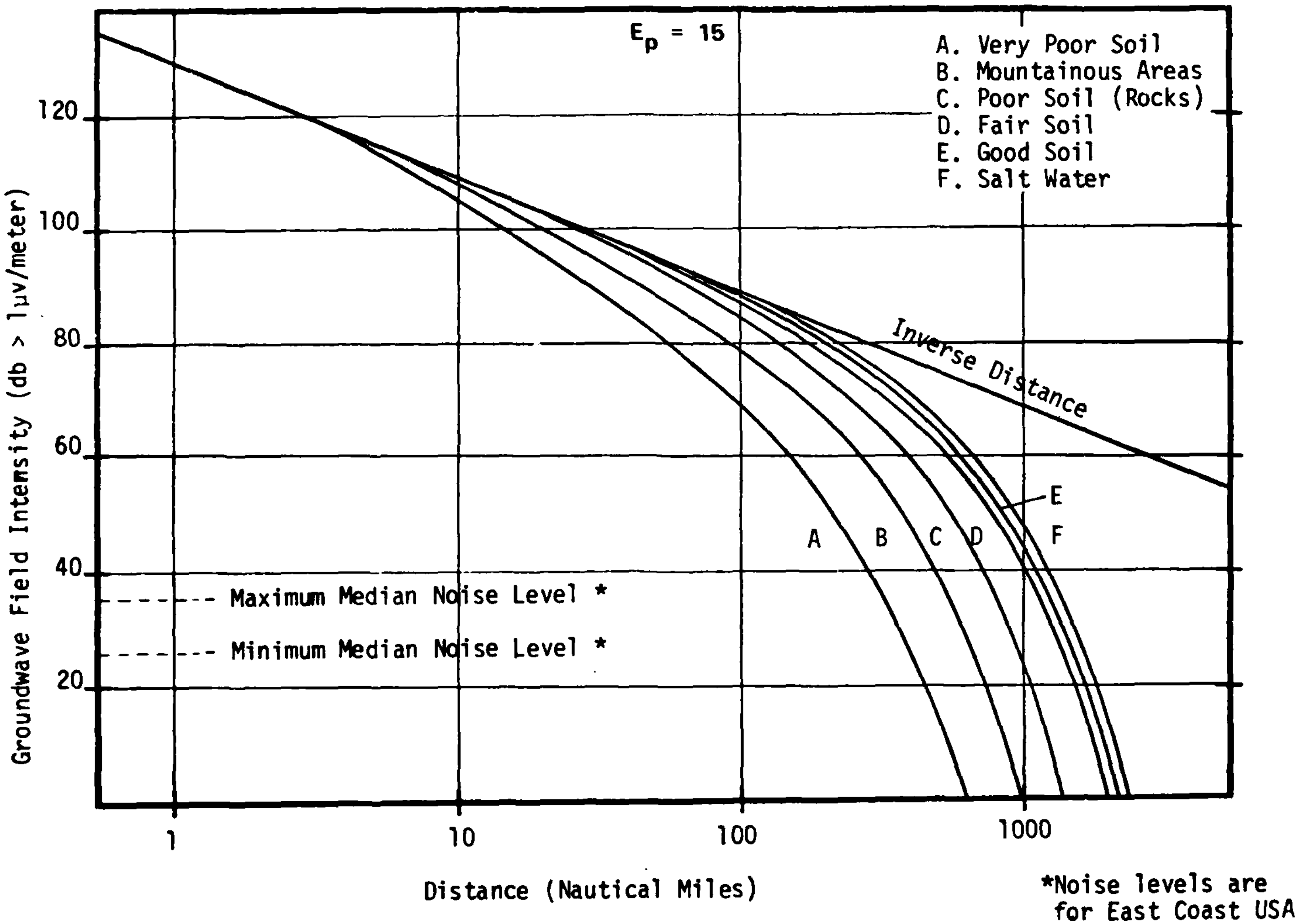


Figure 10. LORAN Field Intensity (300 kW Radiated Power)

The geometric error depends in part on the crossing angle of the LOPs, which in turn depends on the relative location of the transmitters. A decrease in the crossing angle results in an increase in the magnitude of the operationally significant miss distance. For example, assuming that a TD measurement error results in equal LOP errors, i.e., $\Delta LOP_X = \Delta LOP_Y = 695$ ft, the ground distance error or miss distance is 983 ft for LOP crossing angles of 90^{o} and 5325 ft for LOP crossing angles of 15^{o}, the latter being 5.418 times the former.

Contours of ground distance errors per time differences can be drawn on maps to scale the service area in terms of position accuracy. Typical contours are 300, 500, 800, and 1000 meters per microsecond. Figure 11 illustrates accuracy contours for a LORAN star chain configuration.

Expected accuracy and coverage area for military LORAN-C/D receivers are functions of signal-to-noise ratio (S/N) at the receiver input. For all areas but those of extremely high radio frequency interference (RFI), such as central Europe, the ambient noise level is usually below 80 microvolts per meter root mean square (RMS) measured in the LORAN spectrum of 90-110 kHz. Under these conditions, a minimum specified S/N performance of -12 dB for a receiver translates to a signal input of 20 microvolts per meter measured at the peak of the LORAN pulse. Assuming also an effective receiving antenna vertical length of one meter and a propagation path over fair soil, one can use the curve illustrated in figure 10 to predict limits to LORAN coverage for different transmitter powers, as shown in table 3. If the propagation path is other than fair soil, or the ambient noise is increased above the assumed 80 microvolts per meter RMS, or the receiver specified performance is different than -12 dB S/N, then the maximum range will be affected accordingly.

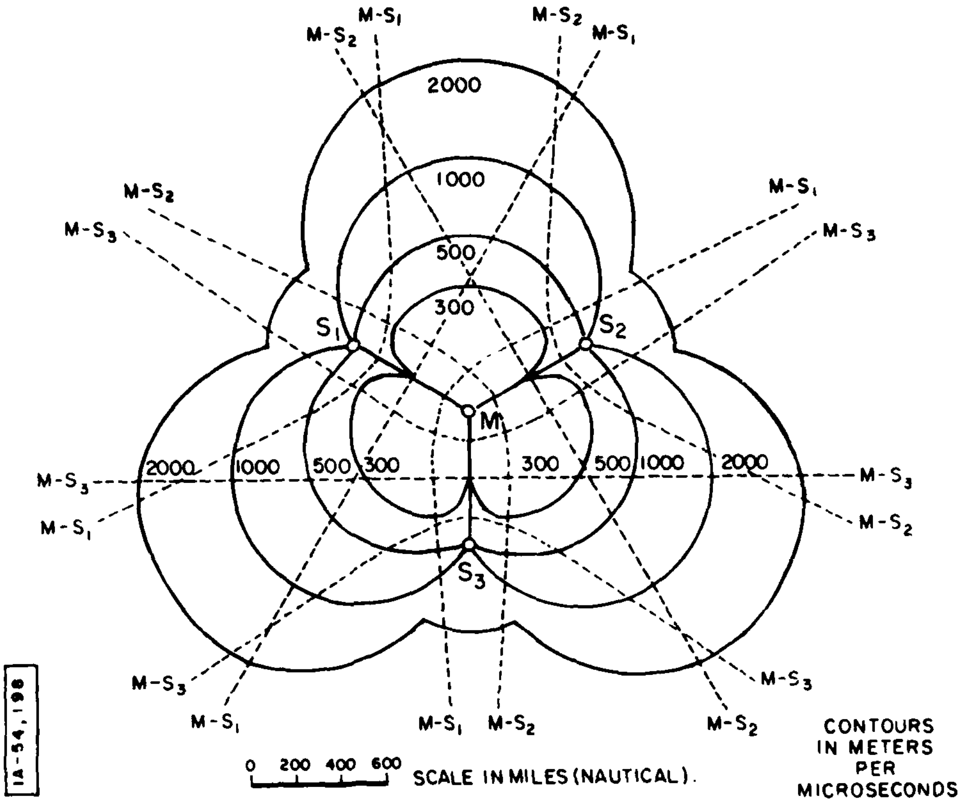


Figure 11. Accuracy Contours for a LORAN Star Chain

Table 3

LORAN Coverage Limits

Transmitter Power (kW)	Range Limit* (nm)
30	650
300	1200
1000	1500

*-12 dB S/N, 80μv noise, fair soil.

3 Signal Characteristics

LORAN signals consist of a nominal carrier at 100 kHz and sideband components representing the essential frequency components of the pulse modulation waveform. The total out-of-band energy is less than 0.5 percent, and of this the energy above 110 kHz and the energy below 90 kHz are each kept less than 0.25 percent of the total radiated energy. The definition of the LORAN spectrum limits was illustrated in figure 3. Thus, the LORAN signals are 20 kHz bandwidth, P9 type emissions transmitted on a 100 kHz carrier.

3.1 LORAN Pulse

The LORAN carrier waveform is a distorted sine wave with a rapidly rising and more slowly decaying envelope superimposed upon it, as shown in figure 12. These pulses are transmitted in a train of 8 or 16 pulses, with the pulses repeating every 1000 or 500 μsec as illustrated in figure 7.

IA-54,199

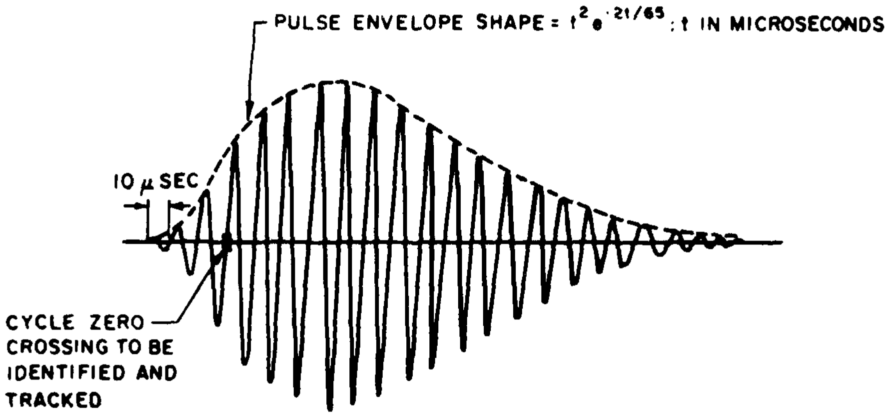


Figure 12. LORAN Pulse

Because all LORAN-C and LORAN-D stations operate on the same frequency, each station is assigned a pulse train repetition rate or group repetition interval (GRI), and the signals are then transmitted using a time-ordered multiplex technique. Simultaneous reception of multiple LORAN chains is termed cross-rate, or mutual, interference.

The effective radiated power (ERP) of a transmitted LORAN pulse is defined as the RMS value of the peak half cycle of the antenna current squared, times the radiation resistance of the antenna. At the receiver, the LORAN signal level is defined as the RMS voltage of a continuous wave (CW) signal having the same peak-to-peak amplitude as the LORAN cycles at the peak of the LORAN pulse.

The LORAN pulse is described by the following equation:

$$V(t) \begin{cases} = 0, \ t < o \\ = V_o \left(\dfrac{t}{t_p} \exp \left(1 - \dfrac{t}{t_p} \right) \right)^2 \sin (\omega t + PC), \end{cases}$$

where $V(t)$ = voltage amplitude of the LORAN envelope,

V_o = voltage at the peak of the pulse,

t = time from the start of the pulse,

t_p = time of the peak of the pulse,

ω = radian frequency of 100 kHz ($2\pi \times 10^5$),

PC = phase code parameter (o or π).

Practical considerations, and the fact that propagation introduces phase modulation, shifts the relationship of the pulse envelope to the cycles of

the 100 kHz carrier. This shift is called envelope-to-cycle discrepancy (ECD) and must be kept less than 5 microseconds (1/2 cycle) for proper processing by the LORAN receiver.

To avoid skywave contamination, the LORAN-C pulse is sampled on the leading edge, 30 microseconds after pulse beginning. Because of the smaller coverage area of LORAN-D, the skywave problem is usually less severe, and sampling may be done later in the pulse to achieve better signal levels. The actual LORAN-D sampling point is determined by receiver design and coverage area, but it is now normally set to either 30 or 40 microseconds after pulse beginning.

The time accuracy with which the reference zero crossing is controlled by the transmitter is ±0.05 microsecond for LORAN-C and ±0.01 microsecond for LORAN-D.

3.2 LORAN Coding

Each pulse of the group may have its carrier frequency in phase or 180 degrees out of phase with an established reference frequency. The pulse phase code is chosen to identify positively the master and slave transmissions for automatic signal acquisition, and also to cancel the effects of long-delayed (greater than 500 μsec) skywave pulse trains by using codes with only one autocorrelation peak. Figure 13 illustrates the standard LORAN-C and LORAN-D phase codes. The LORAN-D code has the LORAN-C code contained on the odd pulses (1, 3, 5, etc.) over two GRIs.

The standard LORAN-C and LORAN-D phase codes were designed many years ago by trial and error to satisfy the requirements for skywave rejection and autocorrelation. Once these requirements were met, the codes were exploited by designers of LORAN receivers. Different properties of codes are used in the following areas:

LORAN-C Phase Code

Period	Master 1	Master 2	Master 3	Master 4	Master 5	Master 6	Master 7	Master 8	Master 9	Slave 1	Slave 2	Slave 3	Slave 4	Slave 5	Slave 6	Slave 7	Slave 8
1	+	+	-	-	+	-	+	-	+	+	+	+	+	+	-	-	+
2	+	-	-	+	+	+	+	+	-	+	-	+	-	+	+	-	-

LORAN-D Phase Code

MASTER PULSES

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	+	+	+	+	-	+	-	-	+	+	-	+	+	-	-	+
2	+	+	-	+	-	+	+	-	+	-	+	-	+	+	+	-
3	+	-	+	-	-	-	-	+	+	-	-	-	+	+	-	-
4	+	-	-	-	-	-	+	+	+	+	+	+	+	-	+	+

SLAVE PULSES

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	+	+	+	-	+	+	+	+	+	-	-	+	-	+	+	+
2	+	-	-	+	+	-	-	-	+	-	+	+	-	+	-	+
3	+	-	+	+	+	-	+	-	+	+	-	-	-	-	+	-
4	+	+	-	-	+	+	-	+	+	+	+	-	-	-	-	-

Figure 13. Illustration of the LORAN-C and LORAN-D Phase Codes

Note: + = 0°
- = 180°

- Signal sampling,
- Search data evaluation,
- Signal detection and verification,
- Long-delayed skywave estimation,
- Cycle selection (linear receivers).

The standard phase codes are compatible and the autocorrelation function of both codes is complementary. This means that the summation of delayed code states equals zero except for the central correlation spike. The LORAN phase code is not a continuous code. The LORAN pulse transmissions are followed by almost one GRI of waiting time before that station transmits again. This type of transmission is processed in the receiver as a series of delayed impulse responses that is unique to LORAN. The phase code provides a significant processing gain against synchronous CW and protection from mutual (cross-rate) interference from other LORAN chains. These properties of the LORAN phase code are presented as part of the discussion of receiver tracking.

3.3 LORAN Communications

The LORAN transmitters have the capability for very low data rate communication by phase shift keying (PSK) the LORAN pulses. The PSK code is designed so that there is no long-term offset or bias in the time-of-arrival measurement. Thus, the navigation accuracy of LORAN is not affected by the LORAN communications. LORAN navigation receivers do not process the PSK communications, and the communications are primarily used as backup for other long-range, high frequency (HF) communication systems used for remote control of LORAN transmitters.

There are many PSK techniques that can be used with LORAN. The two following techniques are in general use with the USCG LORAN-C transmitter chains:

- Clarinet Pilgrim communications with ± 45 degree (± 1.25 microsecond) phase shift, last 6 pulses modulated and all stations of a chain modulated identically each GRI.
- Coast Guard communications with ± 27 degree (± 0.75 microsecond) phase shift, last 2 pulses (or first 2 pulses if Clarinet Pilgrim also used) modulated and all stations of a chain modulated identically each GRI.

4 LORAN Receiving Systems

The following subsections describe typical LORAN receiver functions. All receivers built since 1968 employ both envelope and cycle matching (CM) techniques. Other receivers have been built, or adapted from LORAN-A, to use certain portions of the LORAN-C system; however, those receivers are not described here. Most LORAN receivers designed prior to 1970 used a combination of manual envelope (visual with an oscilloscope) matching and automatic cycle tracking. With the advent of digital computers, large-scale integration (LSI) technology, and more recently the application of micro-logic and micro-computers, all recent receiver designs are fully automatic in their operation.

The LORAN receiver must distinguish the specified LORAN signals from ambient noise and interfering signals. To accomplish this function, the receiver incorporates three basic modes:

- A search mode to identify the requested LORAN chain,
- A lock-on mode to establish signal acquisition, and
- A track mode to determine the time difference and maintain continuity of position determination.

4.1 Signal Processing

4.1.1 Frequency and Bandwidth

LORAN receivers are fixed-tuned to a center frequency of 100 kHz. Acceptance bandwidths between 3 dB and 6 dB points are approximately 25 kHz and 33 kHz, respectively. This large bandwidth is used to insure that the relative amplitude and phase of the essential spectral components of the received pulses are not significantly altered by the tuned circuits of the receiver.

4.1.2 Filtering

There are four basic methods for selective filtering of desired signals and rejection of undesired signals. They are

- Temporal filtering,
- Frequency filtering,
- Spatial filtering, and
- Polarization filtering.

Temporal filtering is achieved when the receiver samples a time window that is less than the total time interval (the GRI). During acquisition, a receiver samples for LORAN pulses in windows between 200 and 1000 microseconds. For this case the power ratio of the time windows provides from 11 to 18 dB of noise discrimination. During the track mode the receiver samples the LORAN pulse centered within a 50 nanosecond time window. This increases the noise discrimination to approximately 47 dB.

In the frequency domain, most LORAN receivers have front end filters that are dynamically adjusted to notch out unwanted narrowband signals appearing within the LORAN passband. This is in addition to the integration in the time domain, which results in discrimination of about 47 dB against wideband noise, as described above. Typical automatic notch filters provide from 40 to 60 dB of notch depth, and have a 2 kHz bandwidth at the 3 dB points. In addition, interference and noise are minimized by narrowband tracking servos. Working in conjunction with sampling error detectors, the rf energy is converted to direct current employing digital methods to produce a very narrow bandwidth. The result is a comb-shaped filter spectrum that attenuates single-frequency interference components falling between the teeth, and reduces broadband interference and noise in the ratio of

comb-tooth width to comb-tooth spacing. Spacing of the LORAN spectral lines as a result of signal processing in the receiver is determined by the LORAN GRI and the length of the phase code in GRI, as follows:

$$F_s = \frac{1}{n \times GRI},$$

where n = length of phase code in GRI (2 or 4),

GRI = LORAN group repetition interval in seconds,

F_s = spectral line spacing in Hz.

The LORAN spectral lines are at frequencies that are the sum and differences of the 100 kHz carrier and the line spacing (F_s). The spectral lines are modified by the rf acceptance bandwidth of the receiver, the phase code impulse function, and the convolution process within the receiver.

If any interference signal is "coherent," it places energy in the receiver so that a bias is caused by integration in the signal processor. If an interference signal is "synchronous" to LORAN, it has a spectral line coinciding with a LORAN spectral line and also is present in time so that it can be integrated by the signal processor. It will be shown in the discussion on receiver tracking that a signal may be coherent and "near synchronous" and still produce the effects of synchronous interference, if the coincidence of a spectral line is less than four times the bandwidth of the receiver tracking loop. Airborne receivers have sampling rates in the 2-5 second category, while ground receivers are usually in the 5-10 second category. Those rates correspond to line spectra coincidences of ≤ 0.08 Hz and ≤ 0.03 Hz, respectively. Airborne receivers with dynamic signal tracking loops inherently provide some additional discriminatory filtering in the frequency domain by following Doppler-shifted signals to shifted spectral positions.

Spatial filtering in azimuth can be applied to a limited degree by employment of a directional receiving antenna. However, the use of this type of antenna requires external inputs of azimuth and altitude for the antenna switching algorithms, which are normally not available to most LORAN receivers.

Polarization filtering is not possible for two reasons. First, the very long wavelength of LORAN at 100 kHZ (3000 meters) requires a very high vertical transmitting antenna for efficiency. This results in a system that is designed for vertical polarization and cannot be easily changed. Second, the horizontal component of a 100 kHZ signal propagated over the ground is severely attenuated and absorbed by the ground in a very short distance.

4.1.3 Amplification

There are two generic types of receivers, linear and hard-limiting. The distinction between them is shown graphically in figure 14. In the case of linear receivers, the raw errors and the processed errors are the same except as modified by gain or attenuation. Linear amplification receivers use automatic or manual gain control to adjust the level of the signals from all stations so that they are all the same amplitude at the sampling gates. The gain control adjustment must be done in conjunction with the groundwave location process to ensure proper receiver operation. Linear amplification tends to offer greater signal dynamic range, but is sensitive to noise and cross-rate interference.

In hard-limited receivers, the processed errors are simply the sign of the error. Hard-limited (HL) amplification is generally applicable only

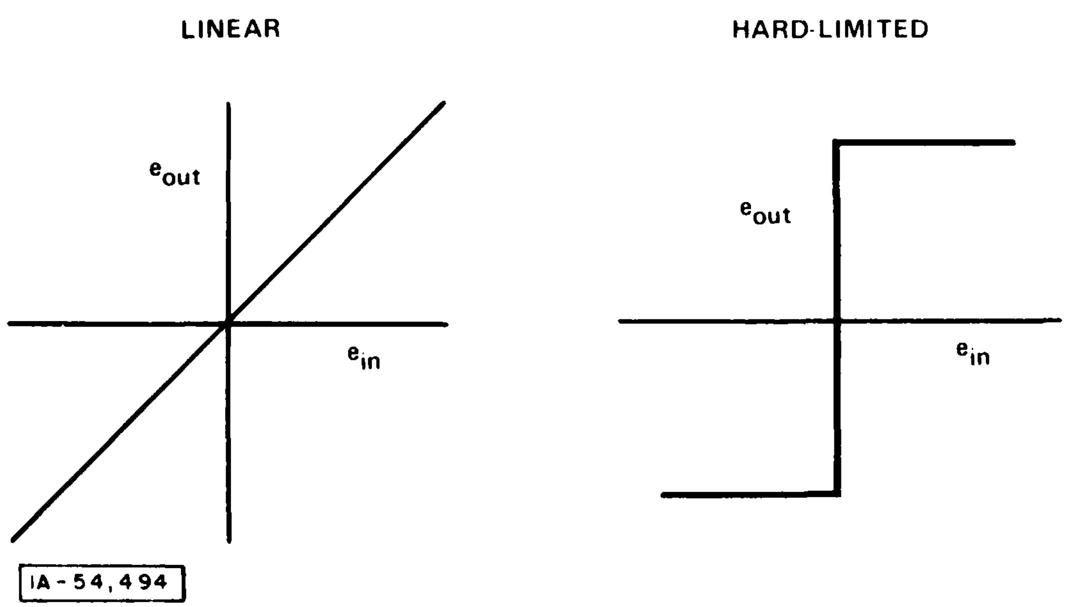


Figure 14. Types of LORAN Signal Processing

to sets with coherent detection and automatic processing. HL simplifies the receiver, tends to limit the dynamic range because all signals receive the same amplification, and permits circuits to be optimized for a selected part of the gain curve. HL is relatively insensitive to burst noise and cross-rate interference, but may be affected by CW interference.

4.1.4 Detection

LORAN receivers use coherent detection by signal integration applied to all pulses of a group. This signal-processing method permits

- operation at low signal-to-noise ratios (S/Ns),
- measurement of carrier phase,
- rf processing of the pulse envelope,
- S/N improvement by integrating all pulses in a group.

4.1.5 Acquisition

The following are design approaches to providing for the initial acquisition of a LORAN chain by the receiver:

(a) All-station acquisition - Once the operator has selected the chain, the receiver will acquire the master and all secondaries having sufficient S/N (practically, this number is limited to 2 to 6 secondaries). The operator may select the display of only those time differences (TDs) of interest.

(b) Limited automatic acquisition - The master and a limited number of secondaries (usually 2) will be acquired, and the operator must set controls that initialize the TDs of interest.

(c) Segmented automatic acquisition - The acquisition process resembles limited automatic, except that the operator can cause one or more secondary tracking intervals to revert to acquisition status to acquire a new secondary, without causing the master interval to revert to acquisition status. This feature is useful when one moves to a part of the coverage area where a different secondary has more favorable geometry than one of those being tracked, or when the station goes off the air.

(d) Manual acquisition - This design approach is generally associated with combined LORAN-A and LORAN-C, and older LORAN-C receivers that use diode detection of signals. Manual acquisition with such receivers requires a higher S/N than is provided by the Coast Guard at the limits of the coverage area. Closer in the signals are generally adequate, but crossing-rate signals may be a problem. Manual acquisition in a coherent detector-equipped receiver is improved by decoding signals on the oscilloscope, but long ranges and cross-rate signals remain a limitation.

4.2 Time Difference Measurements

4.2.1 Groundwave Selection

A location process is used to assure that the groundwave signal from each station is used in the measurement of time differences. In an automatic receiver, after acquisition the circuits sample the signals from each station and the receiver must differentiate between skywave and

groundwave signals. In a manual receiver, the operator is likewise not sure initially whether the signals found are groundwave. However, since the groundwave is always the first signal arriving at the receiver, it is identified by the method of looking earlier in time until no signal can be found, and then moving forward and locking on the first detectable signal, which can be presumed to be the groundwave.

The available sampling techniques to identify groundwave signals are as follows:

(a) Guard sampling - Electronically looking or guard sampling in front of the pulses while continuing to track with signal samples. Moving both the guard and signal sampling circuits earlier in time until the guard sampling detects no signal assures that the signal sampling is on the groundwave. Although this technique adds complexity to the receiver, it permits continuous checking not only for groundwaves, but also for interference.

(b) Sequential sampling - Sequentially stepping forward on the pulse until the sampling sees no signal at all, and then returning to the earliest time at which signal was detected. Sequential sampling is simpler in hardware than guard sampling, but requires more time to assure that the groundwave has been found.

(c) Manual gain adjustment - After the operator finds signals, increasing the rf gain of the receiver while monitoring the oscilloscope for groundwave signals in front of the signal acquired.

4.2.2 Reference Timing

All LORAN sets have internal timing circuits that are referenced or synchronized (manually or automatically) to the received signals. The TD output, which may be displayed by switch positions, by illuminated digital displays, or by coded electrical signals sent to a computer, is actually the TD between the internal timing circuits' references. To achieve accuracy, the internal timing circuits' references must be related exactly to the timing of the received signals. The pulse group time reference (PGTR) process is used to achieve synchronization, and all timing is referenced to the same cycle in every LORAN pulse. As the LORAN system evolved, a number of different cycle identification techniques have been developed. Fundamental to each method is the use of sample strobing to confine detection to a small portion of the pulse. The following is a list of reference timing techniques:

(a) Derived envelope (DE) - A method of electronically altering the received signal so that it has an easily measurable reference time. This is done by differentiating the detected envelope and filtering to produce a zero crossing near the desired tracking cycle. This reference time is compared to the rf signal, and the nearest appropriate carrier zero crossing is selected by the receiver as the tracking point for its time reference. Errors in tracking the DE of greater than 5 microseconds will result in rf carrier tracking errors that are multiples of 10 microseconds. The reason is that the receiver force tracks the phase of

a single cycle; more than 5 microseconds of envelope error changes the sign of the phase error, and the receiver jumps one cycle (10 microseconds at 100 kHz). The DE may be formed by the following methods: first derivative, second derivative, envelope plus the first derivative, and envelope delay and add. Examples of these techniques are given in figure 15. DE is used in hard-limited and the more sophisticated linear amplifier receivers, and is generally associated with automatic receivers. There is significant variation in the design and performance of DE circuits in various receivers, as this function is the most susceptible to atmospheric noise and to incorrect adjustment.

(b) Ratio sampling (RS) - Similar to DE, but only used in linear receivers. This technique requires that the peak of the 100 kHz half cycles on the leading edge of the pulse be measured. These measurements are used to compute the slope of the leading edge of the pulse. The desired tracking point can be determined as a function of the unique slope at each point on the pulse. Ratio sampling may be used in manual receivers if a supplemental meter is provided for the display. Performance is subject to the same limitations as with derived envelope.

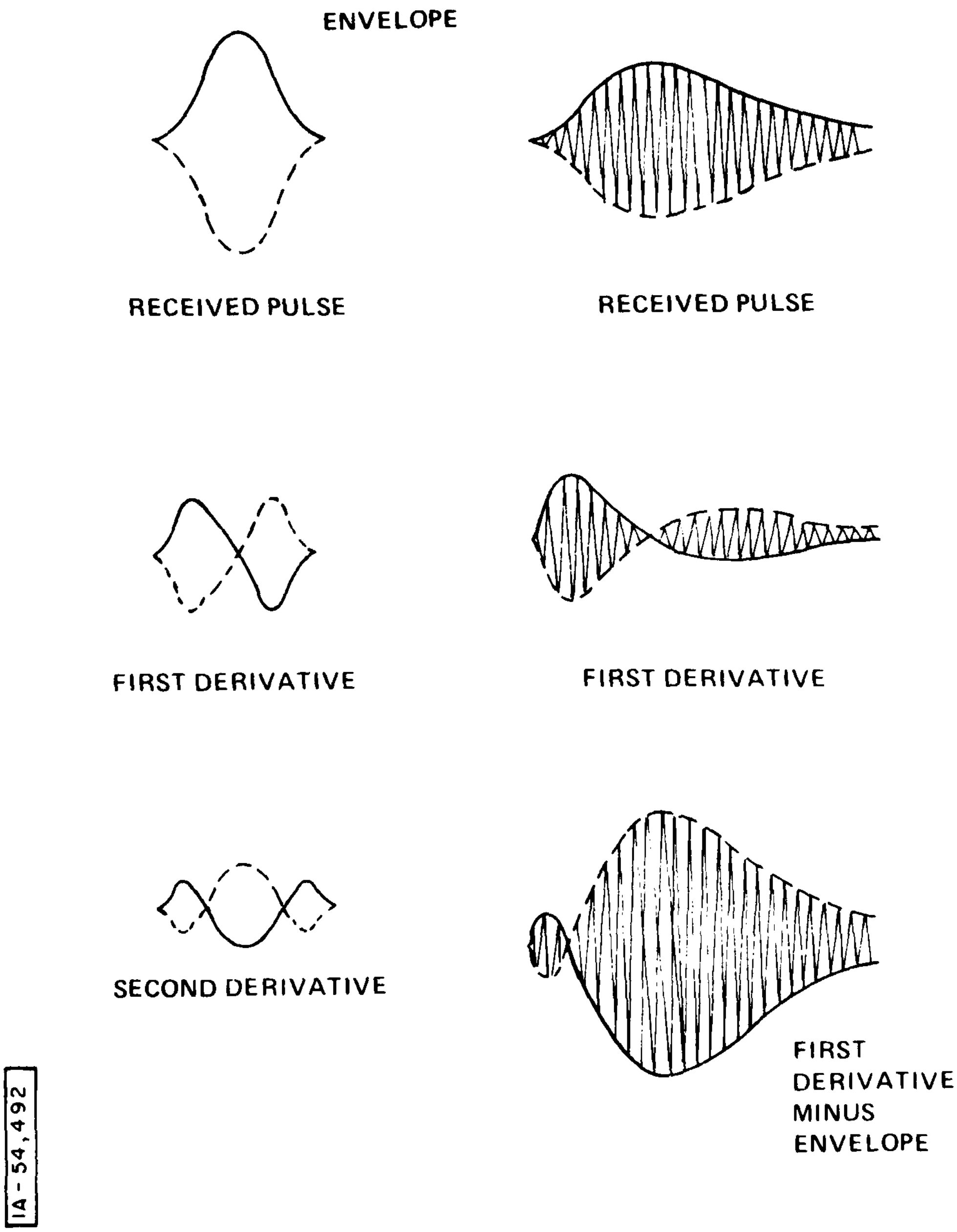


Figure 15. Examples of Derived Envelope Techniques

(c) Envelope matching (EM) - A manual operation requiring that the operator, after completing groundwave location, adjust the receiver gain and timing controls to match the shape of the leading edge of the master station signal and the secondary station signal, by overlaying them on the oscilloscope display. This process requires +6 to +10 dB signal-to-noise ratio and is very sensitive to the receiver front end bandwidth, to skywave interference, and to operator training and experience.

(d) Cycle matching (CM) - Requires first that EM be accomplished with less than 5 microseconds error. Then the operator displays the rf signals and obtains a fine grain adjustment of timing by trying to overlay the master and secondary signals. This technique is subject to the same multiples of 10 microsecond errors as are DE and RS.

4.2.3 Tracking

Automatic tracking or manual matching are the final steps in obtaining TD information from a receiver. Automatic tracking uses electronic circuits to sample, store, and average the tracking errors. Usually all pulses in each pulse group from each station are integrated, effectively increasing the S/N of the samples. The average tracking errors are used to correct the receiver time references, which then generate the TD outputs on servos, electronic displays, or as signals to a computer. This process is repeated frequently, and continuously updated TDs are always available. The averaging ability of automatic tracking is substantially greater than the matching ability of a human operator observing signals on an oscilloscope. Also the oscilloscope usually presents only one of the 8 (or 16)

pulses in the group from each station. For these reasons, matching-type receivers do not perform as accurately or at as long ranges as tracking receivers. Receivers that use manual search and automatic tracking will usually track at long ranges, but should the signals be lost for any reason, will not reacquire because the signal levels will be below those required for manual search.

The automatic tracking process consists of a time-of-arrival (TOA) phase measurement and a cycle selection measurement. The cycle selection techniques are dependent on the generic receiver and the design philosophy. In general, this process is intended to select the desired cycle in the LORAN pulse for the TOA measurement. The TOA measurement is affected by coherent interference, and different processing techniques are used in the LORAN receiver to improve performance. The LORAN phase code itself provides a significant processing gain against synchronous CW, as shown below:

$$\frac{1}{G} = \frac{P - N}{P + N} ,$$

for $P - N \neq 0$

where G = receiver processing gain,

P = number of 0° phase LORAN pulses in a code interval,

N = number of 180° phase LORAN pulses in a code interval.

From this relationship, the standard phase codes provide the following voltage processing gains:

LORAN-C 1/G = 1/4 or 12 dB,

LORAN-D 1/G 1/8 or 18 dB.

The standard phase codes are not considered optimum. First, the codes are <u>not</u> balanced. The summation of all code states (bits) is not equal to zero (no DC offset when integrated). This feature produces a bias

during receiver integration that limits the achievable processing gain. If the phase codes were balanced, the receiver could maximize the voltage processing gain. The LORAN phase codes also have a unique impulse response called the phase code function (PCF). The PCF is processed in the receiver and modulates the radio frequency spectral lines. The PCF of the standard LORAN phase codes does not have deep nulls, and in fact never reaches zero magnitude at a LORAN spectral line. Without zeros or deep nulls in the PCF, the LORAN phase codes will not provide protection from mutual (cross-rate) interference by other LORAN chains. This concept is explained in greater detail in Appendix B.

4.3 Position Fixing

A LORAN position fix is determined by the intersection of at least two LOPs. For navigational purposes, the location of the point of intersection must be translated into geodetic coordinates related to a ground position. The translation is accomplished by plotting LORAN TDs on a map or by computing the distances from the receiver to the LORAN transmitters and converting those distances into geodetic coordinates (latitude/longitude), based on a knowledge of the location of the transmitters.

4.3.1 Time Difference Plotting

Initially, LORAN position fixes were obtained by superimposing hyperbolic TD lines on existing maps and reading the coordinates of their intersection. Navigation done by plotting TD fixes on a map overlaid with a LORAN grid is not the most accurate use of LORAN positioning information. High-resolution maps provide geodetic errors of about 300 to 500 feet. On less accurate regional maps the geodetic error of TD plotting can be as large as 2000 feet.

4.3.2 Coordinate Conversion

The drawbacks to the TD plotting method can be overcome by mathematically converting the LORAN TDs to latitude and longitude. This coordinate conversion allows the LORAN TDs to be used directly for position and navigation. In some current LORAN receiver systems, coordinate conversion computations are performed in high-speed digital computers. The computation converts TDs into geographic latitude and longitude or military universal transverse mercator (UTM) coordinates.

Some coordinate conversion methods have been designed around a polynomial curve procedure that fits known TDs to known geographics. Approximations of the spherical earth solution in this method can result in errors over the relatively small portions of the earth covered by a single LORAN system. Either a second- or third-order polynomial can be used to convert directly from TDs to geodetic coordinates. The coefficients of the polynomials may be determined by measurements, theory, or hybrid techniques. This method is preferred with ground systems whose low mobility limits them to small areas.

The most rigorous coordinate conversion is an iterative method, whereby TDs are estimated and compared with measured values. The geographics are adjusted until the position fix is found with the prescribed accuracy. This method is preferred on systems where the probability of rapidly changing LORAN coordinates is high. One application of this method is described in the following paragraphs. It is used by the AN/ARN-92 and AN/ARN-101 LORAN navigation systems.

The application described here requires that an initial geodetic position be assumed or provided by an outside source. The accuracy of that initial guess is not critical because the iterative method corrects the assumed position. The accuracy of this method is limited by the accuracy to which the estimated TDs can be calculated. The calculation requires

- very accurate distance and azimuth calculations from the reference (assumed) position of the LORAN receiver to each of the LORAN transmitters,
- very accurate estimates of the secondary phase factor to correct for LORAN warpage.

The distance and secondary phase information for each LORAN station is used to calculate a total propagation time or time of arrival (TOA) of each LORAN transmitter at the receiver:

$$T_{(\ )} = T_{ps} + T_{cs} \quad ,$$

where $T_{(\ )}$ = time of arrival (TOA) from the designated transmitter (M, A, B) to the receiver position,

T_{ps} = primary wave contribution $\dfrac{\text{distance}}{\text{wave propagation velocity}}$ *

T_{cs} = secondary phase contribution calculated from a polynomial equation or a look-up table. Values of T_{cs} are usually less than 4 microseconds.

---

*Wave propagation velocity in air (n_a = 1.000338)
299.6912000 meters per microsecond
983.2388595 feet per microsecond

LORAN TDs are then calculated from the above TOAs and the slave emission delays (EDs) as follows:

$$TD(\,) = TOA_{(\,)} - TOA_M + ED_{(\,)} \quad ,$$

where $TD(\,)$ = estimated time difference for the designated master-slave pair, i.e., TDA or TDB,

$TOA_{(\,)}$ = total propagation time of the designated slave $T_{(\,)}$, A or B,

TOA_M = total propagation time of the master station, M,

$ED_{(\,)}$ = emission delay for the designated slave transmitter (ED = coding delay + baseline length).

The coordinate conversion process now differences TDs from a LORAN receiver with the TDs calculated above and uses the errors in a gradient calculation. The gradients of LORAN TDs are defined as the differential rates of change of Cartesian position with respect to changes in time differences. Gradients of the LORAN TDs are calculated from the LORAN transmitter azimuths at the receiver position and expressed in the following matrix equation, which is accurate for a limited region in the vicinity of the reference position:

$$\begin{bmatrix} d_x \\ d_y \end{bmatrix} = \frac{C_p}{\Delta} \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} d_{TDA} \\ d_{TDB} \end{bmatrix} \quad ,$$

where d_x = change in north-south position

d_y = change in east-west position

C_p = nominal wave propagation velocity

$A = \sin \psi_B - \sin \psi_M$

$B = \sin \psi_M - \sin \psi_A$

$C = \cos \psi_M - \cos \psi_B$

$D = \cos \psi_A - \cos \psi_M$

$\Delta = BC - AD$ (matrix determinant)

$\left.\begin{matrix} d_{TDA} \\ d_{TDB} \end{matrix}\right\}$ = difference in the observed and estimated TDs

$$d_{TD\_} = \left(TD_{OBS} - TD_{EST}\right) \quad .$$

The changes in Cartesian position (d_x, d_y) are converted to changes in latitude and longitude and used to update the assumed initial reference position. The new reference position is then used to estimate a new set of TDs, and the process continues in an iterative manner until either a maximum number of iterations is completed or the error is minimized to a predetermined limit.

4.4 Currently Available Receivers

LORAN receivers fall into either of two classes, depending on whether they were designed for commercial application or military usage. Commercial units have been used successfully in military applications, while the much higher cost of military units usually prohibits their commercial use. A recent survey of commercially available LORAN receivers indicated that

there are 13 suppliers of over 26 different models, ranging in price from \$1,000 to \$6,000. Military receivers have been developed to satisfy specific operational requirements and applications, and their costs generally range from \$25,000 to \$100,000. Table 4 lists some of the military LORAN receivers in current use by the Army and Air Force.

Table 4

Military LORAN Receivers in Current Usage

Nomenclature	Mode	Operation Manual/Automatic	Application
AN/APN-70	C	M	RC-135, C-130, P-3
AN/APN-151	C	M	RC-135, C-141, H-3
AN/APN-157	C	M	RC-135, C-141
AN/APN-199	C/D	A	C-5A
AN/ARN-70	C	M	C-130E
AN/ARN-78	C	M	C-130H
AN/ARN-92	C/D	A	F-4D, RF-4C, F-105, B-52, DC-130H
AN/ARN-101	C/D	A	F-4E, RF-4C, Others
AN/ARN-109	C	M/A	T-43
AN/ARN-110	C/D	A	Army Helicopters
AN/ARN-114	C/D	A	Cargo Aircraft
AN/PSN-6	C/D	A	Manpack, Vehicle

4.5 Tactical LORAN-C/D Receivers

Modern military LORAN-C/D receivers use computers to enhance different aspects of LORAN signal processing for operation under very severe signal conditions. There are several manufacturers of LORAN equipment for military use, but few of these systems use digital computers, or microprocessors for signal processing. The major LORAN-C/D systems in operation, or production, for tactical military usage are the following:

(a) AN/ARN-92(V) — USAF developed, 1968 technology, linear receiver, computer, and display for use in tactical fighter aircraft. Designed specifically for the F-4D and RF-4C. Versions were developed for the F-105, C-130 and B-52 aircraft.

(b) AN/ARN-101(V) — USAF developed, 1975 technology, linear receiver, computer, and display for use in tactical fighter aircraft. Designed specifically for the F-4E and RF-4C. Other versions are contemplated.

(c) AN/PSN-6 — US Army developed, 1974 technology, hard-limit receiver with microprocessor for portable use by Army field units. Designed for manpack and vehicle (jeep) operations.

The most sophisticated LORAN receiving system is the AN/ARN-101(V). It utilizes the following technical improvements not incorporated in other systems to date:

(a) Three orthogonal H-field (magnetic) antennas. The navigation computer selects the optimum antenna for each station, using aircraft heading and attitude information. This antenna system is immune to the signal loss or distortion associated with the E-field (electrostatic) antennas used with earlier LORAN receivers.

(b) Software implementation of signal sampling and data integration, including search and synchronization, cycle selection, phase tracking, automatic gain control, interference suppression, and rate aiding. The implementation of those processes in software allows the receiver to adapt to varying signal and noise conditions.

(c) Integrated operation with an inertial measurement unit (IMU) through a Kalman filter. The navigation computer processes both the IMU and LORAN data to provide precise position and velocity information. The long-term accuracy of LORAN is used to upgrade the IMU position and velocity every 5 minutes, while the short-term accuracy of the IMU velocity and acceleration is used to rate-aide the receiver tracking loops and limit the variance of the LORAN TDs. This limiting of LORAN positional variance serves to cross-check the LORAN accuracy with the IMU to detect any offset in the LORAN position. When large offsets are encountered, the LORAN is uncoupled from the Kalman filter and the IMU takes over as the navigation sensor. The performance of the hybrid system in high dynamic maneuvers and in the presence of ECM is synergistic, in the sense that the net performance is better than the total performance of the two constituent systems operating independently.

5 Tactical LORAN-C/D Chains

Currently there are 2 versions of tactical LORAN transmitter chains:

- AN/TRN-21, LORAN-D, and
- AN/TRN-38, LORAN-C/D.

They represent the fixed ground electronics part of a deployable hyperbolic navigation system, and are designed to be compatible with LORAN-C and the 407-L/485-L Tactical Air Control Systems.

The AN/TRN-21, the prototype transmitter for the LORAN-D system, was designed, developed, and built in 1966-1968. The chain consists of 4 transmitters with 400-foot towers and a monitor station. Peak radiated power is 6.8 kW. This will produce at least 7.1 millivolts field strength at 100 kilometers, with a LORAN pulse of 80 microseconds time to peak.

The AN/TRN-38 tactical LORAN-C/D chain consists of a minimum of 3 AN/TRN-39 transmitters and one AN/TRN-40 monitor station. The monitor consists of the monitor/synchronizer shelter portion of the AN/TRN-39 and the air conditioning equipment. The AN/TRN-39 transmitters consist of 4 equipment shelters and a 400-foot transportable antenna system. The AN/TRN-38 LORAN system will transmit 30-kW peak radiated power. This will produce at least 16 millivolts field strength at 100 kilometers, using the standard 65 microsecond time to peak LORAN pulse. Pulse format may be either LORAN-D or LORAN-C and may be any of the standard GRIs. Maximum pulse repetition frequency is 533 pulses per second in the double-rate mode, and it is possible to double rate any or all stations so that the resulting navigation grid will be on 2 rates. Each AN/TRN-39 transmitter station contains all of the capability for control of the LORAN grid, so that any one station may assume the monitor function.

BIBLIOGRAPHY

1. Analytical Systems Corp., "Review of Progress in LORAN Navigation," ASCR 72-55, 1972.

2. Jansky and Bailey, Inc., "The LORAN-C System of Navigation," February 1962.

3. National Bureau of Standards, "Phase of the Low Radiofrequency Ground Wave", NBS Circular 573, June 1956.

4. National Bureau of Standards, "Development of LORAN-C Navigation and Timing," NBS Monograph 129, October 1972.

5. Stanford Research Institute, "Mathematical Considerations Pertaining to the Accuracy of Position Location and Navigation Systems," NWRC-RM 34, AD 629609, November 1965.

6. Technology Incorporated, "LORAN-D Systems Planning Guide," May 1973.

7. USAF Aeronautical Chart and Information Center, "Geodesy for the Layman," February 1968.

8. U.S. Coast Guard, "LORAN-C User Handbook," CG-462, August 1974.

9. Wild Goose Association, Proceedings of the Fourth Annual Technical Symposium, "On the Analysis and Minimization of Mutual Interference of LORAN-C Chains," D.A. Feldman et al., USCG, October 1975.

10. Wild Goose Association, "Radionavigation Journal," 1978.

11. Wild Goose Association, "LORAN-C System Characterization," WGA Pub No. 1, September 1976.

Appendix A. LORAN Chain Data*

The information on LORAN chains is provided primarily to indicate coverage areas. The information on U.S. Coast Guard chains is sufficient for use in coordinate conversion models. Before use is made of these systems for navigation, the data should be confirmed and refined.

Privately owned chains are presently in operation in the Gulf of Mexico and Java Sea and planned for operation in the North Sea, Celtic Sea, and Hudson's Bay. The USCG and USAF have installed chains utilizing low-power commercial equipment, to cover, respectively, the St. Mary's River and Southwestern, Southeastern, and Central European test ranges.

The information on planned chains is tentative and must be confirmed with the owner or operator before use is made of the information. In particular, site locations are not confirmed. The names of towns indicate only general areas. Where a latitude and longitude are given, the site location is determined, but the final survey may not have been made.

The latitude, longitude, and baseline lengths herein were furnished by the Defense Mapping Agency, Hydrographic Center and are based upon World Geodetic System — 1972 Datum. Appropriate geodetic satellite shifts have been made to relate these coordinates to the center of the earth. The latitudes and longitudes are listed in units of degrees, minutes, and seconds.

---

*Reprinted by permission from the 1978 Wild Goose Association "Radionavigation Journal."

The following parameters were used by the Coast Guard in the computation of LORAN chain data:

a. Signal propagation: The velocity of light in free space 2.99792458 (10^8) meters/second and an index of refraction of 1.000338 at the surface for standard atmosphere.

b. Phase of the groundwave: As described in NBS Circular 573, June 26, 1956.

c. Conductivity: Sigma = 5.0 mhos/meter (seawater). Baseline electrical distance computations were made assuming a smooth, all-seawater transmission path between stations.

d. Permittivity of the earth, esu: $E_p = 80$ for seawater.

e. Altitude in meters: $h_2 = 0$.

f. Parameter associated with the vertical lapse of the permittivity of the atmosphere: a = 0.75.

g. Frequency: 100 kHz.

h. Spheroid: WGS-72 (equatorial radius (a) = 6,378,135.0 meters, polar radius (b) = 6356,750.5 meters, flattening (f) = (a-b)/a = 1/298.26).

Inquiries pertaining to the LORAN-C system should be addressed to:

Commandant (G-WAN-3/73)
U.S. Coast Guard
Washington, D.C. 20590

The information contained in the following pages supersedes the information contained in the "LORAN-C User Handbook" published by the Coast Guard (CG-462) August 1974.

Northwest Pacific Chain - Rate 9970 (SS3)

Station	Coordinates Latitude & Longitude	Station Function	Coding Delay & Baseline Length	Radiated Peak Power
Iwo Jima, Bonin Is.	24-48-04.10N 141-19-29.00E	Master	. . .	1.8 MW
Marcus Is.	24-17-07.70N 153-58-51.50E	W Secondary	11,000μs 4283.94μs	1.8 MW
Hokkaido, Japan	42-44-37.00N 143-43-09.06E	X Secondary	30,000μs 6685.12μs	400 kW
Gesashi, Okinawa, Jap.	26-36-24.99N 128-08-56.21E	Y Secondary	55,000μs 4463.18μs	400 kW
Yap, Caroline Is.	09-32-45.66N 138-09-55.23E	Z Secondary	75,000μs 5746.79μs	1.5 MW

Central Pacific Chain - Rate 4990 (S1)

Station	Coordinates Latitude & Longitude	Station Function	Coding Delay & Baseline Length	Radiated Peak Power
Johnston Is.	16-44-43.95N 169-30-31.20W	Master	. . .	300 kW
Upolo Pt., Hawaii	20-14-49.16N 155-53-09.70W	X Secondary	11,000μs 4972.23μs	300 kW
Kure, Hawaii	28-23-41.77N 178-17-30.20W	Y Secondary	29,000μs 5253.17μs	300 kW

North Pacific Chain - Rate 9990 (SS1)

Station	Coordinates Latitude & Longitude	Station Function	Coding Delay & Baseline Length	Radiated Peak Power
St. Paul Is., Pribiloff Is., Alaska	57-09-09.88N 170-14-59.81W	Master	. . .	300 kW
Attu, Alaska	52-49-45.05 173-10-52.31E	X Secondary	11,000μs 3875.32μs	300 kW
Port Clarence, Alaska	65-14-40.12N 166-53-14.47W	Y Secondary	29,000μs 3069.09μs	1.0 MW
Narrow Cape, Alaska	57-26-20.21N 152-22-11.22W	Z Secondary	43,000μs 3590.10μs	400 kW

Gulf of Alaska Chain - Rate 7960 (SL4)

Station	Coordinates Latitude & Longitude	Station Function	Coding Delay & Baseline Length	Radiated Peak Power
Tok, Alaska	63-19-42.81N 142-48-31.90W	Master	. . .	400 kW
Narrow Cape, Alaska	57-26-20.21N 152-22-11.22W	X Secondary	11,000μs 2804.45μs	400 kW
Shoal Cove, Alaska	55-26-20.85N 131-15-19.65W	Y Secondary	26,000μs 3651.14μs	400 kW

West Coast Canadian Chain - Rate 5990 (SH1)

Station	Coordinates Latitude & Longitude	Station Function	Coding Delay & Baseline Length	Radiated Peak Power
Williams Lake BC, Canada	51-57-58.78N 122-22-02.24W	Master	. . .	400 kW
Shoal Cove, Alaska	55-26-20.85N 131-15-19.65W	X Secondary	11,000μs 2343.60μs	400 kW
George, Washington	47-03-47.99N 119-44-39.53W	Y Secondary	27,000μs 1927.36μs	1200 kW

U.S. West Coast Chain - Rate 9940 (SS6)

Station	Coordinates Latitude & Longitude	Station Function	Coding Delay & Baseline Length	Radiated Peak Power
Fallon, Nevada	39-33-06.62N 118-49-56.37W	Master	. . .	400 kW
George, Washington	47-03-47.99N 119-44-39.53W	W Secondary	11,000μs 2796.90μs	1.2 MW
Middletown, California	38-46-56.99N 122-29-44.53W	X Secondary	27,000μs 1094.50μs	400 kW
Searchlight, Nevada	35-19-18.18N 114-48-17.43W	Y Secondary	40,000μs 1967.30μs	500 kW

Great Lakes Chain (operational 2/80) - Rate 9930 (SS7)

Station	Approximate Latitude & Longitude	Station Function	Coding Delay & Baseline Length	Radiated Peak Power
Dana, Indiana	39-51-07.54N 87-29-12.14W	Master	. . .	400 kW
Malone, Florida	30-59-38.74N 85-10-09.30W	W Secondary	11,000μs 3355.11μs	1.0 MW
Seneca, New York	42-42-50.60N 76-49-33.82W	X Secondary	28,000μs 3162.06μs	1.0 MW
Baudette, Minnesota	48-33N 94-32W	Y Secondary	44,000μs	1.0 MW

Southeast U.S.A. Chain - Rate 7980 (SL2)

Station	Latitude & Longitude	Station Function	Coding Delay & Baseline Length	Radiated Peak Power
Malone, Florida	30-59-38.74N 85-10-09.30W	Master	. . .	1.0 MW
Grangeville, Louisiana	30-43-33.02N 90-49-43.60W	W Secondary	11,000μs 1809.54μs	1.0 MW
Raymondville, Texas	26-31-55.01N 97-50-00.09N	X Secondary	23,000μs 4443.38μs	400 kW
Jupiter, Florida	27-01-58.49N 80-06-53.52W	Y Secondary	43,000μs 2201.88μs	300 kW
Carolina Beach, N Carolina	34-03-46.04N 77-54-46.76W	Z Secondary	59,000μs 2542.74μs	700 kW

U.S. East Coast Chain - Rate 9930 (SS7) (Shutdown 10/79)

Station	Coordinates Latitude & Longitude	Station Function	Coding Delay & Baseline Length	Radiated Peak Power
Carolina Beach, NC	34-03-46.04N 77-54-46.76W	Master	. . .	700 kW
Jupiter, Florida	27-01-58.49N 80-06-53.52W	W Secondary	11,000μs 2695.51μs	300 kW
Cape Race, Newfoundland	46-46-32.18N 53-10-28.16W	X Secondary	28,000μs 8389.66μs	1.8MW
Nantucket, Massachusetts	41-15-11.93N 69-58-39.09W	Y Secondary	49,000μs 3541.31μs	300 kW
Dana, Indiana	39-51-07.54N 87-29-12.14W	Z Secondary	65,000μs 3560.72μs	400 kW
Electronics Engineering Center Wildwood, NJ	38-56-58.22N 74-52-01.57W	T Secondary	82,000μs 2026.21μs	200 to 400 kW

Northeast U.S.A. Chain (reconfigured 9/78) - Rate 9960 (SS4)

Station	Approximate Latitude & Longitude	Station Function	Coding Delay & Baseline Length	Radiated Peak Power
Seneca, New York	42-42-53N 76-49-35W	Master	. . .	1.0 MW
Caribou, Maine	46-48-27.20N 67-55-37.71W	W Secondary	11,000μs 2797.20μs	350 KW
Nantucket, Massachusetts	41-15-11.93N 69-58-39.09W	X Secondary	25,000μs 1969 93μs	300 KW
Carolina Beach N. Carolina	34-03-46.04N 77 54 46 76W	Y Secondary	39,000μs 3221.65μs	700 KW
Dana, Indiana	39 51 07.54N 87 29 12 14W	Z Secondary	54,000μs 3162 06μs	400 KW

North Atlantic Chain - Rate 7930 (SL7)

Station	Coordinates Latitude & Longitude	Station Function	Coding Delay & Baseline Length	Radiated Peak Power
Angissoq, Greenland	59-59-17.27N 45-10-27.47W	Master	. . .	1.0 MW
Sandur, Iceland	64-54-26.58N 23-55-21.75W	W Secondary	11,000μs 4068.03μs	1.8 MW
Ejde, Faroe Islands	62-17-59.68N 07-04-26.71W	X Secondary	21,000μs 6803.77μs	400 kW
Cape Race, Newfoundland	46-46-32.18N 53-10-28.16W	Z Secondary	43,000μs 5212.20μs	1.8 MW

Norwegian Sea Chain - Rate 7970 (SL3)

Station	Coordinates Latitude & Longitude	Station Function	Coding Delay & Baseline Length	Radiated Peak Power
Ejde, Faroe Islands	62-17-59.68N 07-04-26.71W	Master	. . .	400 kW
Bo, Norway	68-38-06.15N 14-27-47.00E	X Secondary	11,000μs 4048.10μs	200 kW
Sylt, Germany	54-48-29.80N 08-17-36.33E	W Secondary	26,000μs 4065.64μs	300 kW
Sandur, Iceland	64-54-26.58N 23-55-21.75W	Y Secondary	46,000μs 2944.53μs	1.8 MW
Jan Mayen, Norway	70-54-52.61N 08-43-58.69W	Z Secondary	60,000μs 3216.30μs	200 kW

Mediterranean Sea Chain - Rate 7990 (SL1)

Station	Coordinates Latitude & Longitude	Station Function	Coding Delay & Baseline Length	Radiated Peak Power
Simeri Crichi, Italy	38-52-20.61N 16-43-05.96E	Master	- - -	200 kW
Lampedusa, Italy	35-31-20.88N 12-31-29.96E	X Secondary	11,000μs 1755.98μs	400 kW
Kargabarun, Turkey	40-58-20.95N 27-52-01.52E	Y Secondary	29,000μs 3273.30μs	200 kW
Estartit, Spain	42-03-36.49N 03-12-15.90E	Z Secondary	47,000μs 3999.69μs	200 kW

Central European Chain - Rate 4970 (S3), USAF, Loran-D

Station Name	Location	Function Power	Coding Delay & Baseline Length	
Baumholder, Germany	49-36-18.813N 07-19-38.277E	Master	. . . . . .	
Hokes Mook, Germany	53-39-13.867N 08-43-46.508E	X Sec.	11,000μs 1536.37μs	5 kW
Eching, Germany	48-15-48.929N 11-37-49.263E	Y Sec.	25,000μs 1160.70μs	5 kW
Wincompe, England	50-00-40N 02-10-30W	Z Sec.	34,000μs 2309.41μs	5 kW

Southeast US Chain(Test) - Rate 3970 (L3) USAF, Loran-C/D

Station Name	Location	Function Power	Coding Delay & Baseline Length	
Ft. McClellan, Alabama	33-44- 85-56-	M		
Kisatchie, Louisiana	31-05-42N 92-34-06W	X	11,000μs 1798.82μs	
Raiford, Florida	30-05-15 82-11-43	Y	25,000μs 2304.00μs	

Note: This chain is not operational for navigation useage. The X & Y slaves have been shutdown while the Master remains as a test transmitter.

Fort Hood Chain - Rate 4970 (S3), US Army, Loran-D

Station Name	Location	Function Power	Coding Delay Baseline Length	
Summerville, Texas	30-20-11.966N 96-32-32.826W	Master 150 W	- - - - - -	
Canyon Lake Texas	29-54-22.512N 98-13-40.627W	X Sec. 150 W	11,000μs 498.982μs	
Navarro Mill Dam, Texas	31-57-36.960N 96-41-18.163W	Y Sec. 150 W	23,000μs 600.134μs	

Note: This chain is intermittant. Check with the monitor station or Fort Hood before using.

Utah (RPV Test) Chain - Rate 4970 (S3), USAF, Loran-D

Station Name	Location	Function Power	Coding Delay Baseline Length	
Little Mountain, Utah	41-14-46.584N 112-13-26.33W	M 125W		
Montello, Nevada	41-16-44.336N 114-09-22-662W	X 125W	11,000μs 541.76μs	
Nephi, Utah	39-44-21.896N 111-51-58.159W	Y 125W	25,000μs 568.77μs	

Note: For information only.

Gulf of Mexico - Rate 4864 - Industrial Radiolocation Service

Station Name	Location	Function Power	Coding Delay Baseline Length	
Perry, Louisiana	29-56-02.416N 92-09-22.019W	Master 200W		
Triumph, Louisiana	29-20-27.564N 89-27-59.844W	X Sec. 100W		
San Louis Pass, Texas	29-05-52.747N 95-06-30.133W	Y Sec. 100W		

Note: For information only.

St. Mary's River Chain - Rate 4930

Station	Coordinates Latitude & Longitude	Station Function	Coding Delay & Baseline Length	Radiated Peak Power
Gordon Lake, Canada	46-24.53089N 83-51.89983W	Master	- - -	100 W
Pickford, Michigan	46-03.88177N 84-21.69366W	X Secondary	11000.045μs 221.652μs	100 W
Drummond Island, Michigan	45-57.23899N 83-37.26612W	Y Secondary	21999.988μs 220.332μs	100 W
Dennis, Canada	46-36.77671N 84-28.91827W	Z Secondary	32999.988μs 227.934μs	100 W

Note: For information only.

Western USSR Chain - Rate 8000 (SLO)

Station	Coordinates Latitude & Longitude	Station Function	Coding Delay Baseline Length	Radiated Peak Power
Oriol	53-56N 36-05E	Master	- - -	500 kW
Petrovavodesk	61-48N 34-19E	W Secondary	10,000μs	500 kW
Kuibychev	53-11N 49-46E	X Secondary	25,000μs	500 kW
Simferopol	44-58N 32-02E	Y Secondary	50,000μs	500 kW
Baranovichi	53-08N 26-01E	Z Secondary	65,000μs	500 kW

Note: For information only.

Appendix B. LORAN Receiver Tracking Model*

LORAN receivers usually employ second-order tracking loops that predict the time of arrival of the next signal. The TOA tracking will contain those errors caused by the coincidence of the LORAN and interference spectral lines not nulled out by the LORAN phase code. This can be shown by considering a mathematical model of a LORAN cross-correlation receiver, if the following assumptions are made in addition to small signal linearity:

(1) The rf pulse can be represented as the product of a low-pass envelope and a single carrier, i.e., there is frequency domain symmetry about the carrier frequency or zero time domain pulse modulation;

(2) The energy in a single pulse is constant;

(3) The phase locked loop (PLL) is a first-order servo loop;

(4) The receiver rf prefilter need not be modeled because it is wide enough that it does not alter the characteristics of the LORAN pulse.

---

*From Wild Goose Association, Proceedings of the Fourth Annual Technical Symposium, "On the Analysis and Minimization of Mutual Interference of LORAN-C Chains," D. A. Feldman et al., USCG, October 1975.

With these assumptions, and the equivalence of time convolution and frequency multiplication, we can write the receiver cross-correlation transform as the product of frequency components:

$$R(\omega) = PCF_T(\omega)\, e^{-j\omega T_s}\, U_o(\omega),$$

where $PCF_T(\omega)$ = phase code function, a sum of + and - impulses defining the appropriate phase code. For LORAN-C* in 2 GRIs,

$$PCF(\omega) = \sum_{k=0}^{7} \alpha_k\, e^{-j\omega k T_p} + e^{-j\omega GRI} \sum_{k=8}^{15} \alpha_k\, e^{-j\omega k T_p},$$

$e^{-j\omega T_s}$ = low-pass LORAN envelope,

$U_o(\omega)$ - a single impulse or delta function at time of zero. An infinite series of such impulses is

$$\frac{\pi}{GRI} \sum_{-\infty}^{+\infty} U_o\left(\omega - \frac{\pi k}{GRI}\right),$$

ω radian frequency

ω_o - carrier, $2\pi \times 10^5$

T_s = initial synchronization time

---

* $PCF(\omega)$ for LORAN-D requires limits of 0-15 and 16-31 plus 2 additional terms to account for the 64 bit LORAN-D code over a 4 GRI period.

T_p pulse spacing in seconds

GRI = group repetition interval in seconds.

The first term, $PCF_T(\omega)$, extends over all frequency and is periodic. The second is the LORAN pulse spectral envelope, which is modulated by $PCF_T(\omega)$, and the last term, $U_o(\omega)$, converts the envelope to discrete line spectra spaced 1/n GRI apart. Each LORAN waveform at a different GRI has this characteristic harmonically related line pattern. The receiver processes interference signals in the same fashion and, if the interference is synchronous, the received signal will contain line spectra $I(\omega)$, similar to $R(\omega)$. The coincidence of these two line patterns and the product of the spectral envelopes at coincidence results in PLL tracking errors. The errors in the tracking PLL transform can be written as

$$E(\omega) = \left[R(\omega) \otimes I(\omega)\right] S(\omega),$$

where $\otimes$ = the convolution operation,

$S(\omega)$ = impulse response of the PLL servo loop.

Most of the line spectra resulting from the interior convolution of the LORAN ($R(\omega)$) and the interference ($I(\omega)$) spectra will fall well outside the bandwidth of $S(\omega)$ and be rejected by the receiver. The only concerns are those line spectra of $I(\omega)$ and $R(\omega)$ that fall within less than four times the -3 dB bandwidth of the PLL ($S(\omega)$), because these are the only convolution products appearing in $E(\omega)$, which is used to adjust the phase tracking strobes of the receiver for time-of-arrival measurements.

GLOSSARY OF ABBREVIATIONS AND ACRONYMS

ASP	Additional secondary phase
CD	Coding delay
CEP	Circular error probable
CM	Cycle matching
CW	Continuous wave
dB	Decibel
DC	Direct current
DE	Derived envelope
ECD	Envelope-to-cycle discrepancy
ED	Emission delay
EM	Envelope matching
ERP	Effective radiated power
ft	Foot
GDOP	Geometric dilution of precision
GRI	Group repetition interval
HF	High frequency
HL	Hard-limited
Hz	Hertz (cycle per second)
IMU	Inertial measurement unit
kHz	Kilohertz
km	Kilometer
kW	Kilowatt
LF	Low frequency
LOP	Line of position

LORAN	Long range navigation
LSI	Large-scale integration
m	Meter
MC	Manual cycle matching
MHz	Megahertz
nm	Nautical mile
nsec	Nanosecond
PCF	Phase code function
PGTR	Pulse group time reference
PLL	Phase locked loop
PSK	Phase shift keying
PTTI	Precision time and time interval
rf	Radio frequency
RFI	Radio frequency interference
RMS	Root mean square
RS	Ratio sampling
S/N	Signal-to-noise ratio
sec	Second
TD	Time difference
TOA	Time of arrival
USAF	United States Air Force
USCG	United States Coast Guard
UTM	Universal transverse mercator
μsec	Microsecond